hi

Day 17, 21.03.2019

Cosmology 3

7 days until opening day

Joe Bonamassa week

housekeeping

Gotta come to class

question about anything?

I'll make a movie for you:

Grades to date: Projects, quizzes, notes in a pdf in the slides area

the rest of your grades are in LON-CAPA or MasteringPhysics

Section 2 folks:

Project has begun in phases:

Document 1: software, introduction, tutorial: due March 22

Document 2: your individual dataset and project instructions: due Final Exam

https://qstbb.pa.msu.edu/storage/QS&BB2019/Homework_Projects/honors_project_2019/MinervaInstructions1_2019.pages.pdf

MasteringAstronomy:

Course ID: MABROCK41459;

free code: WSSPCT-BLIDA-INANE-TOGUE-RIGOT-UNRWA

I configured it wrong. I've extended the due date to Sunday.

March 2019

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
24	25	26	27	28	1	2
3	4	5	6	7	8	9 HW6
10	11	12 lecture	13	14 lecture	15 HW6 due	16 HW7
17	18	19 lecture	20	21 lecture	22	23 HW8
24 HW7 due	25	26 lecture	27	28 lecture	29 HW8 due	30 HW9
31	1	2 lecture	3	4 lecture	5 HW9 due	6

spring break

Eastern Time Time Zone


KEEP
CALM
AND
LET'S
REVIEW

There are a handful of “classic tests”

- Pound Rebka Gravitational Red Shift
- The perihelion of Mercury’s Orbit
- Light bending around the Sun
- “Gravitational Lensing”
- “The Hafele-Keating experiment”
- “Binary Pulsar period”
- Black Holes
- “Gravitational Waves”

in 1915 scientific cosmology didn’t exist

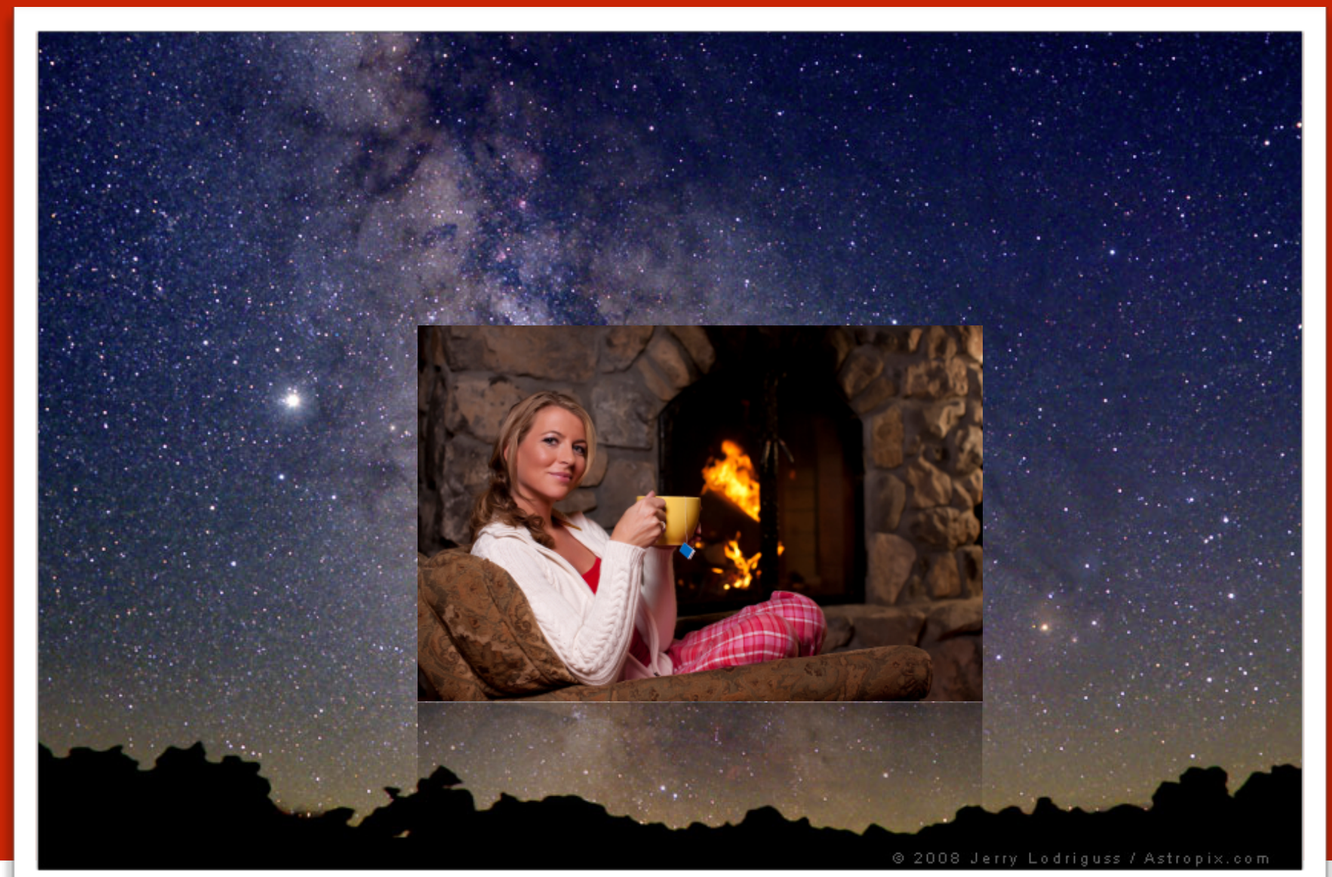
does now.

in 1917 the universe presumed by all to be:

- static, eternal
- limited to the Milky Way

that’s it.

cozy.



Einstein

began the first truly scientific field of cosmology

applying GR (1915) to the entire universe

1917: *Cosmological Considerations in the General Theory of Relativity*

"It exposes me to the danger of being confined to a madhouse."

need a starting point & assumptions

in order to be able to solve the GR equations

Einstein enunciated the “Cosmological Principle”

On the largest scale:

the universe is homogeneous ← the average density of matter is about the same and uniform at all places in the Universe: there are no special places

the universe is isotropic ← the universe looks the same to all observers: there are no special directions

quantitative cosmology

rests on the Cosmological Principle

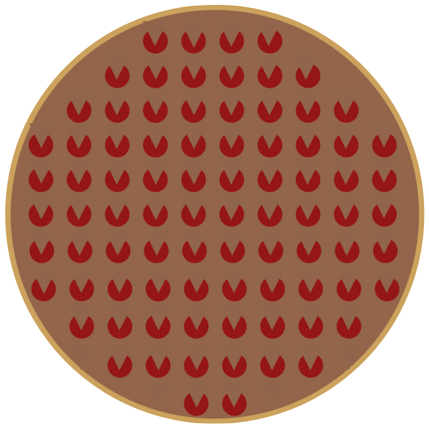
It doesn't matter where you are.

Viewed on sufficiently large distance scales, there are no preferred directions nor are there preferred places in the Universe.

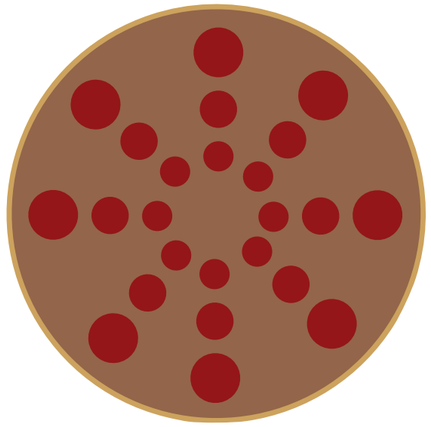
The Universe is presumed to be
homogeneous: average density same & uniform everywhere
and
isotropic: no special directions

my Famous
Probable Planar Pepperoni Pizza Probe

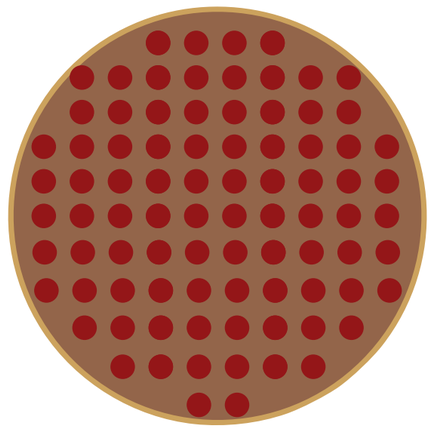
…as viewed from the center:



not isotropic and yet homogeneous



not homogeneous and yet isotropic



homogeneous and isotropic

homogenous?

the only way to calculate!

smear all of the stars (nebulae out) into a dust, or fluid

density, not individual masses, is the meaningful quantity

How good is that approximation?

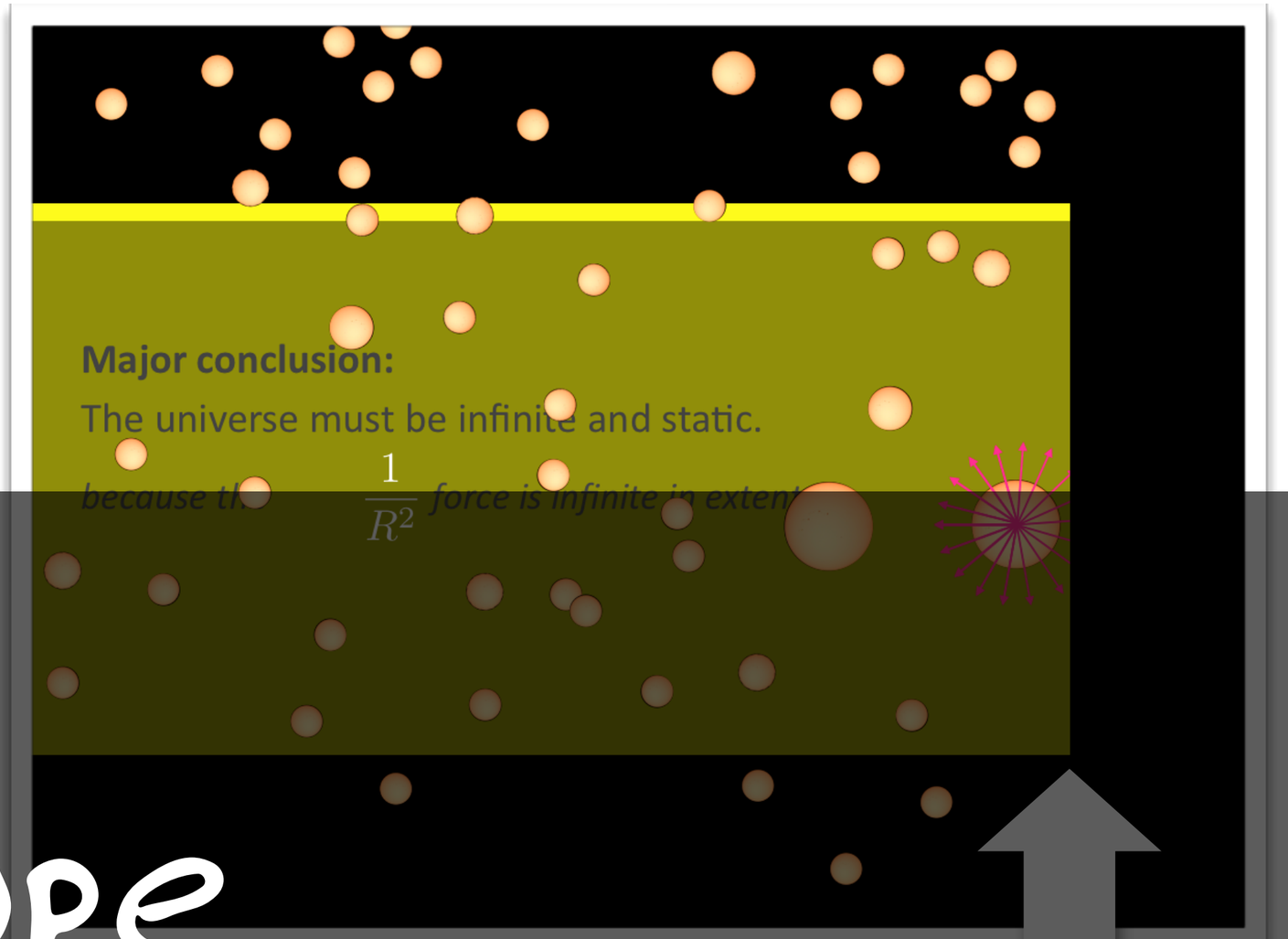
The current density of matter in the universe is about 6 protons/m^3

He was plagued by infinity

He ran into a similar problem that Newton did...

The weird delicate balance of an infinite universe...with an infinite gravitational force on all objects

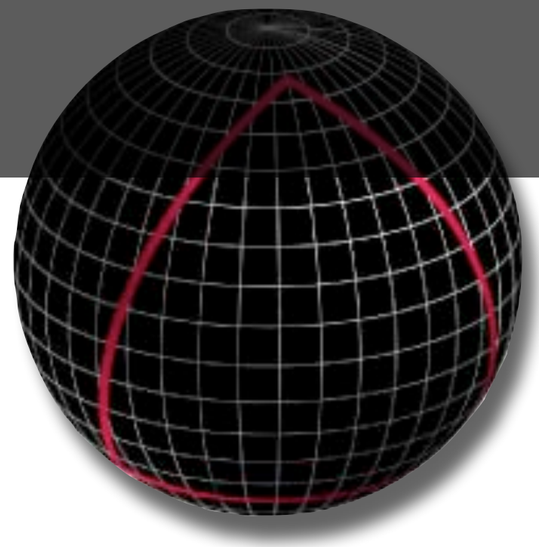
strangely in balance!



But he was smarter than Newton

And he owned a tool to erase infinity!

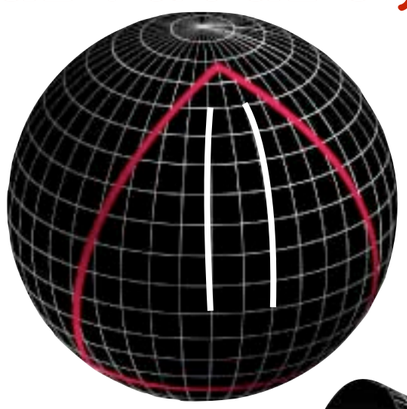
Make use of his geometric-tool and assume enough mass in the whole Universe ***to cause space to bend around on itself...***

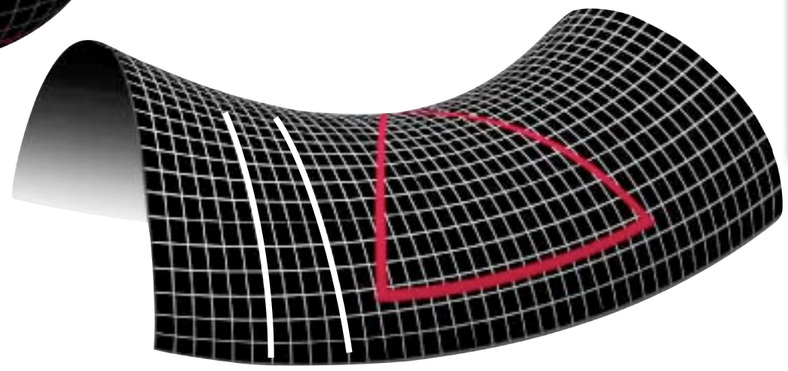


That was his goal:
to get rid of infinity

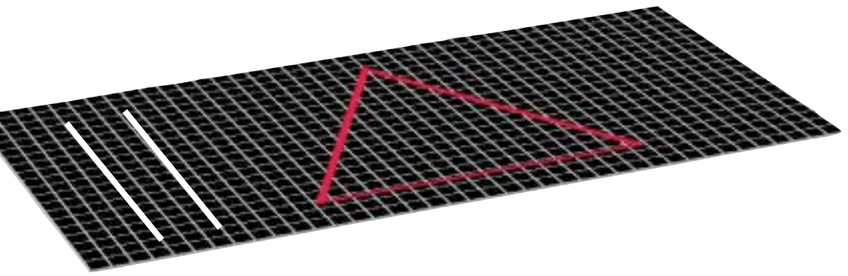
curvature, “k” - hypervolumes

$k = +1,$
positive curvature
finite, unbounded





$k = 0,$ no curvature
infinite, unbounded



$k = -1,$ negative curvature
infinite, unbounded

is impossible to visualize the negative curvature 3d shape...
it’s like a saddle, or mmm
mmm good
Pringles Potato HyperChips

A mathematical fact:
These 3 are the only geometries that can be both homogeneous and isotropic

uh oh

this wasn’t going well

What to do? GR appeared to be right…the Classic Tests!

He mucked with his beloved equation.

the dreaded Cosmological Constant, Λ

> ...if it were certain that the field equations which I have hitherto employed were the only ones compatible with the postulate of general relativity, we should probably have to conclude that the theory of relativity does not admit the hypothesis of a spatially finite universe.
>
> However, the system of equations allows a readily suggested extension which is compatible with the relativity postulate...

geometry $G = T$ energy, pressure, mass

he added a **negative pressure** term...

$$G + \Lambda = T$$

the "**Cosmological Constant**"

a **negative pressure**-like term...that only is relevant on huge scales

> "...the introduction of this second member constitutes a complication of the theory, which seriously reduces its logical simplicity."

Makes the Universe static...not expanding or contracting

later:

"My biggest blunder."

for 2 reasons: Hubble and instability

He believes his to be the only possible solutions

to

$$G = T$$

or

$$G + \Lambda = T$$

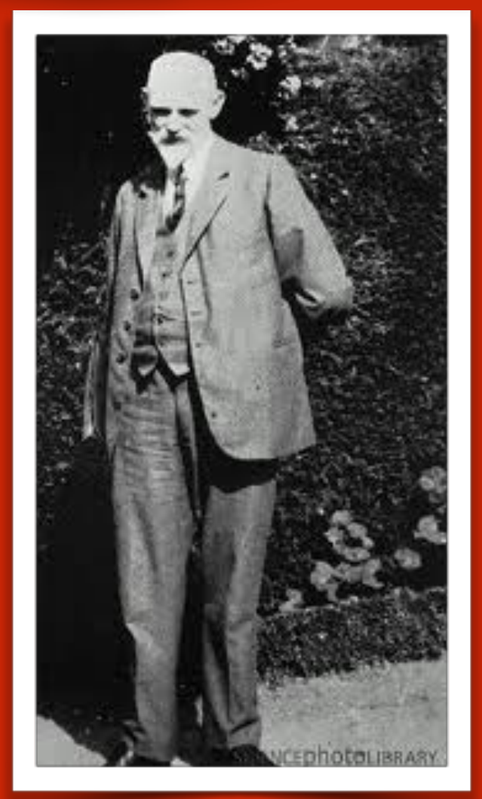
Wrong

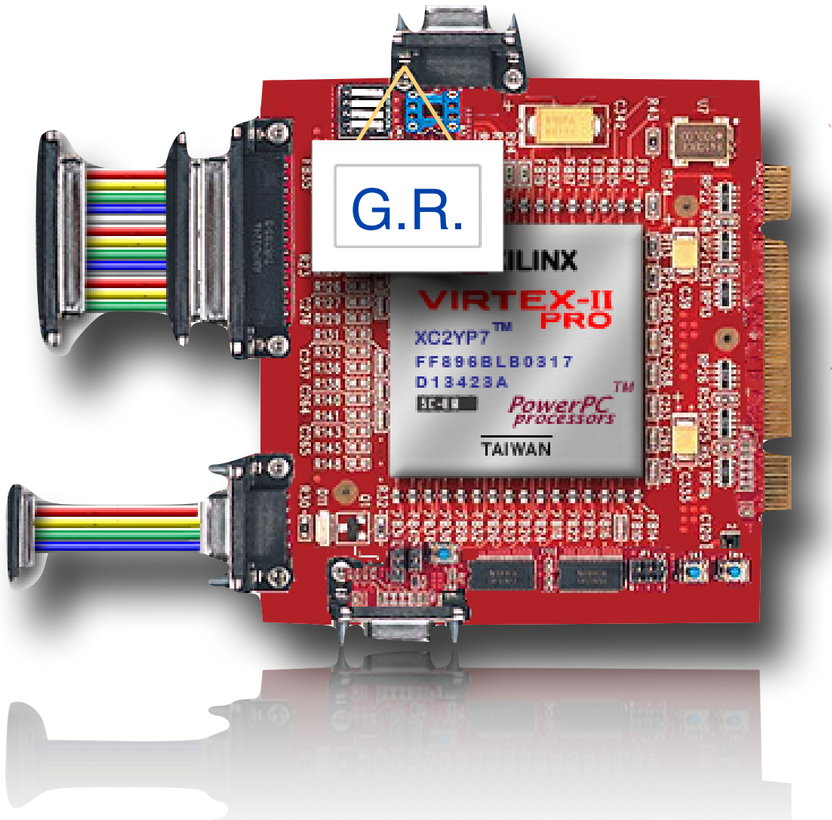
$G + \Lambda = T = 0$ (no matter density)

about the uniqueness of his solution

Willem de Sitter

1917





static.

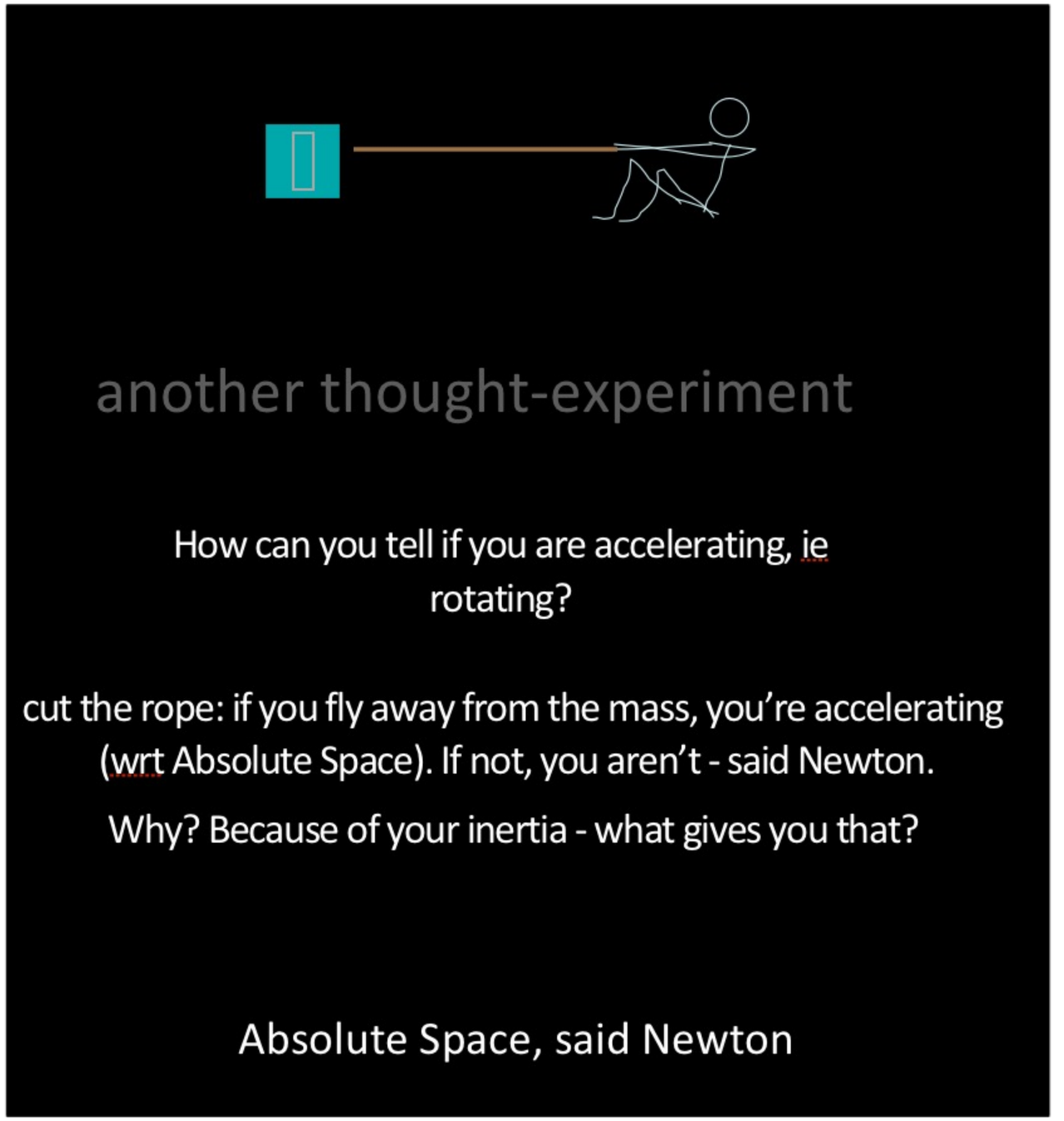
strictly geometry...so, what's the matter?

Now wait a minute… ***NO MATTER in de Sitter's model, empty universe!***

Geometry of spacetime - by itself - actually causes spacetime to bend!! Einstein presumed only matter could do that.

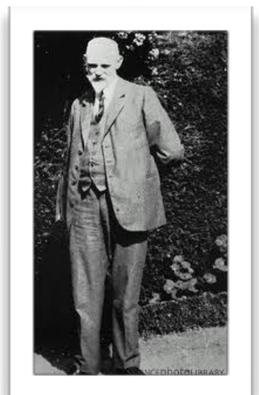
Einstein took it badly...even though colleagues and friends, he was very critical of de Sitter in print

remember the rope and knife?



The Prevailing Wisdom...matter in the Universe accounts for universally accelerated motion.

Einstein fervently believed that...named the idea "Mach's Principle" after his hero in Prague.

Along comes  with a Universe-solution that has NO MATTER, but gravity, nonetheless.

Einstein was convinced that only MATTER could warp spacetime!

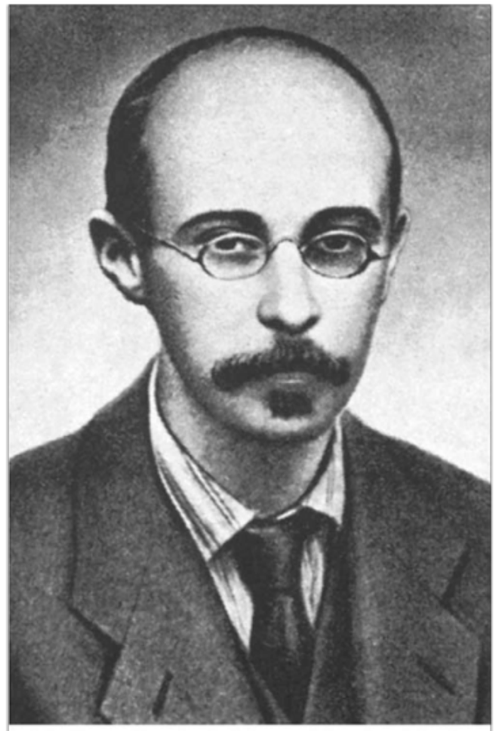
but as Feynman's advisor said many years later:

Alexander Friedman (1888-1925)

in 1922, 23

finds a **whole class** of solutions!

with and without Λ



Adding insult to injury, an unknown mathematical meteorologist from Russia opened The General Relativity Pandora's Box.

$$G = T$$
$$G + \Lambda = T$$

Now, the modern basis of GR solutions:

the "Friedman Solutions"

29 June 1922, submits paper "On the curvature of Space" to to *Zeitschrift für Physik*

Einstein didn't take it well.

> The results concerning the non-stationary world, contained in [this] work, appear to me suspicious. In reality, it turns out that the solution given in it does not satisfy the [general relativity] equations.

18 September 1922

Einstein in a letter of complaint to the premier journal considering publication of Friedman's work

Zeitschrift für Physik

Considering that the possible existence of a non-stationary world has a certain interest, I will allow myself to present to you here the calculations I have made ... for verification and critical assessment. [The calculations are given] ... Should you find the calculations presented in my letter correct, please be so kind as to inform the editors of the Zeitschrift für Physik about it; perhaps in this case you will publish a correction to your statement or provide an opportunity for a portion of this letter to be published.

Friedman to Einstein, 6 December 1922

> In my previous note I criticised [Friedman's work On the curvature of Space]. However, my criticism, as I became convinced by Friedman's letter communicated to me …, was based on an error in my calculations. I consider that Mr Friedmann's results are correct and shed new light.

May 1923

Einstein capitulating later in a letter to *Zeitschrift fur Physik*

> To punish me for my contempt for authority, Fate made me an authority myself.

Einstein in typical bumper-sticker mode. *mea culpa*

Friedman then traveled Europe promoting his work

In July 1925 took a record-breaking 7.4km balloon flight with meteorological instruments

By the end of August he was dead of Typhoid Fever... badly, deliriously lecturing to an imaginary classroom while separated from his pregnant wife.

“Edwin Hubble, I have watched for four years and I have never seen you study for ten minutes." He then paused for what was an awful moment for Edwin, and continued, "Here is a scholarship to the University of Chicago.”

Wheaton, Illinois HS Principal to Edwin Hubble at his 1906 graduation

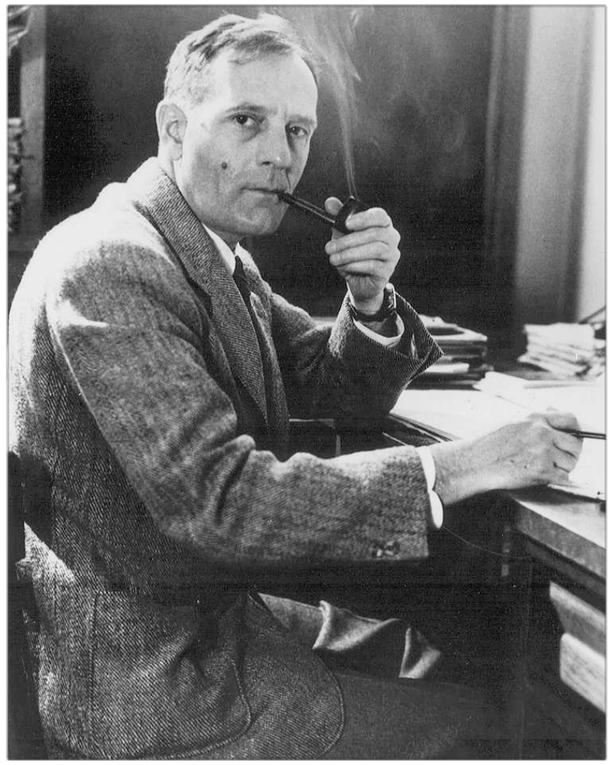
Edwin Hubble 1889-1953

astronomer

discoverer of:

the whole universe

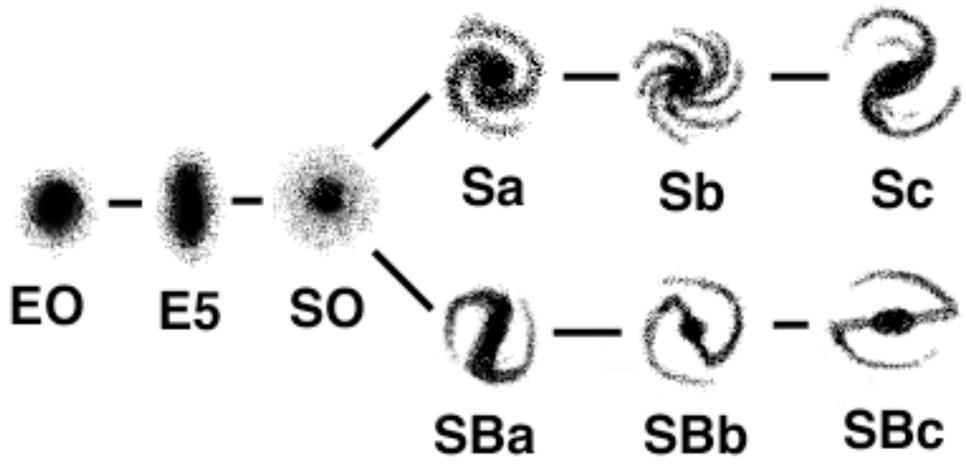
the expanding universe



very systematic thinker/ writer

1922-1926:

Hubble classification scheme for “nebulae”



basically: spherical, elliptical, bar, and irregular

remember HR diagram

"instability" strip

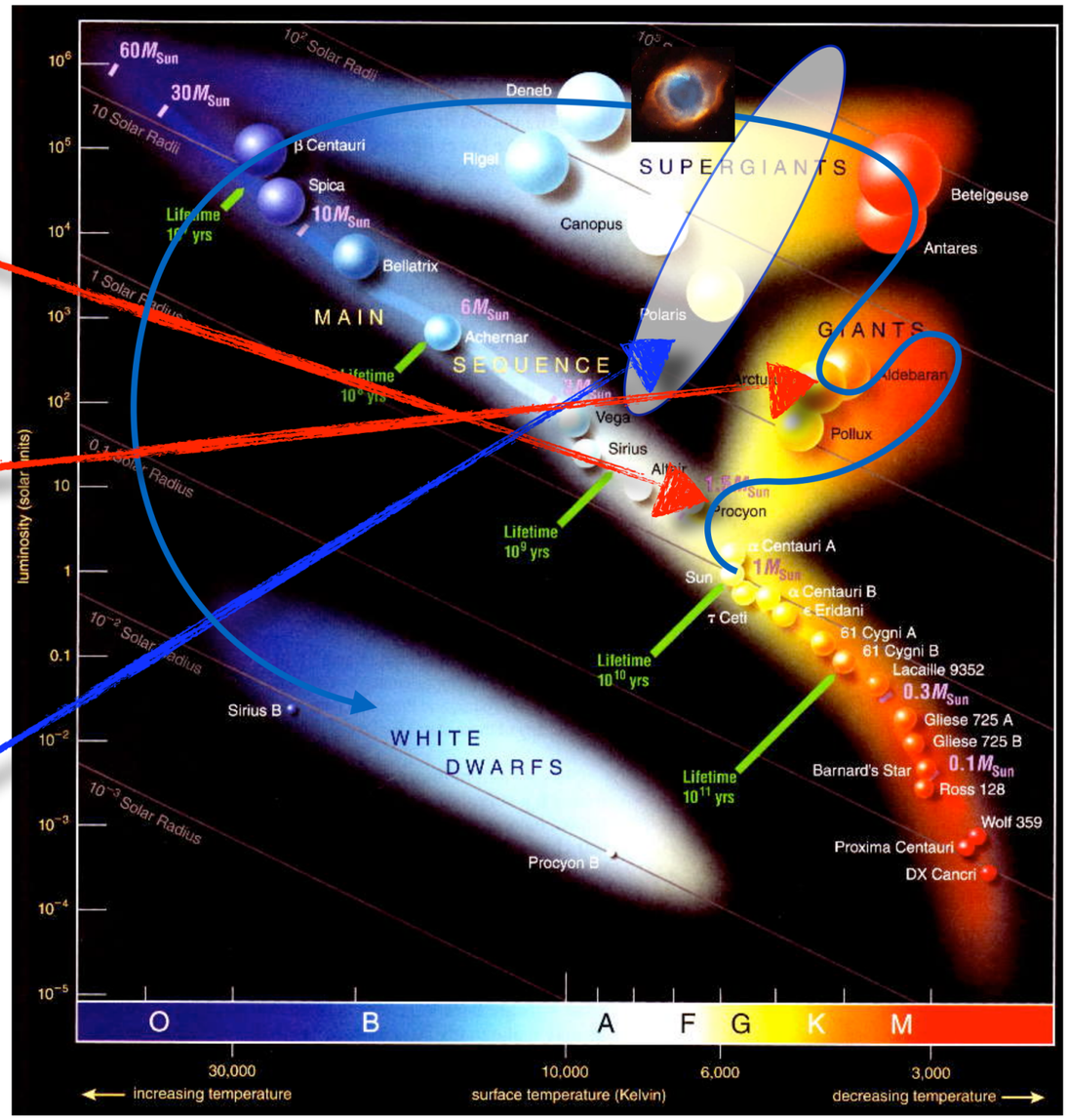
a balancing act

SUN-LIKE?
H → He

SUN-LIKE?
He → C + O

source of Carbon for life

REGION OF INSTABILITY
pulsating stars



distances are hard to determine

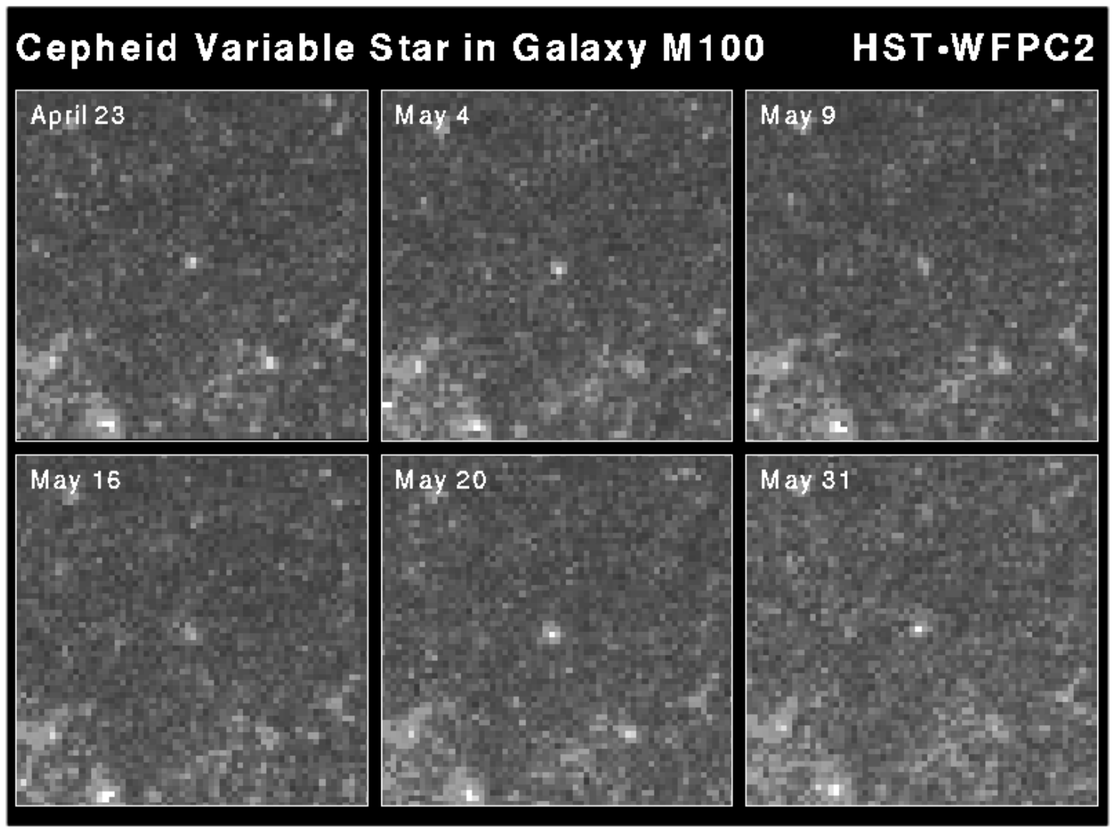
Cepheid Variable stars: the clue to galactic distances

absolute brightness is related to their period

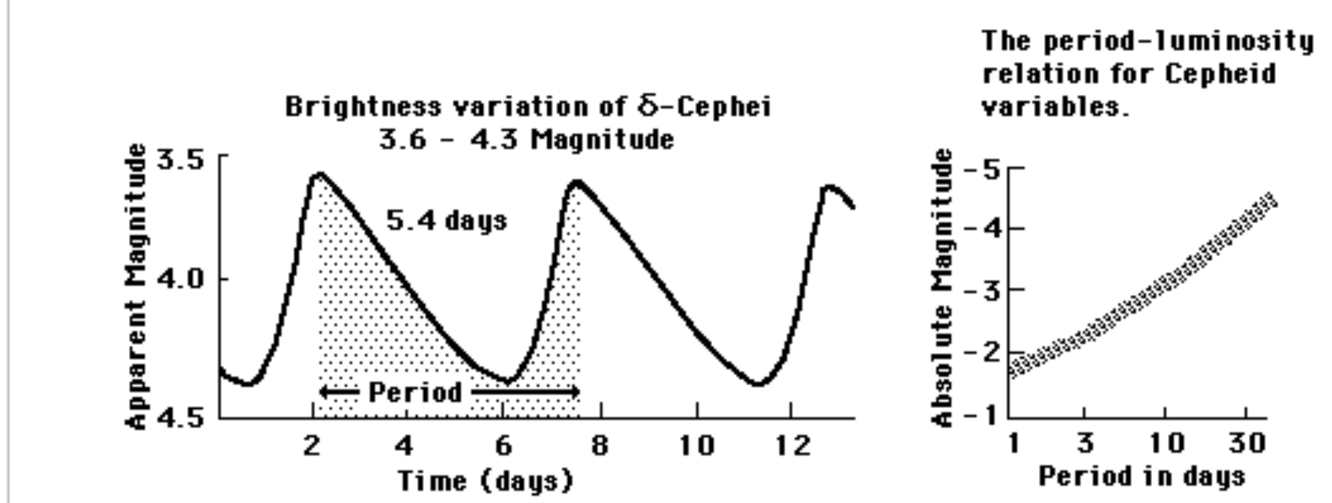
since brightness goes like $1/R^2$ —> distance!

bootstrapping

discovered by Henrietta Leavitt at Harvard



1912



Knowing the absolute amount of light from an object

can calculate the distance

Cepheid Variable Stars are a yardstick

Hubble used Leavitt's formulation

Cepheids were everywhere!

were "nebulae" in the Milky Way?

or, is the universe much bigger?

M31, Andromeda

2900 thousand light years

1924: Andromeda is its own galaxy

That famous public argument ended.

The universe became HUGE... **overnight**!

M33, Triangulum

3000 thousand light years

NGC 6822, Barnard's Galaxy

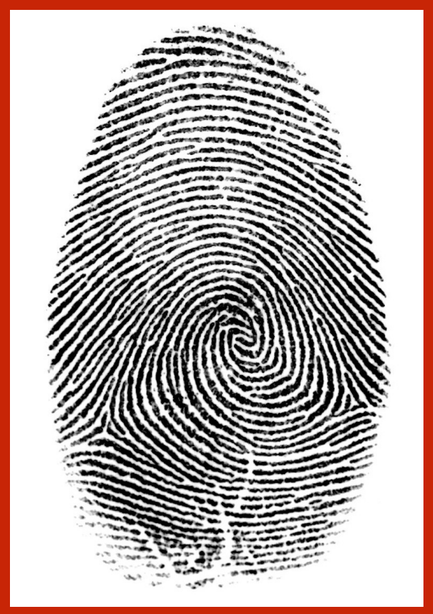
1700 thousand light years

But wait. There’s more.

Hubble was just warming up.

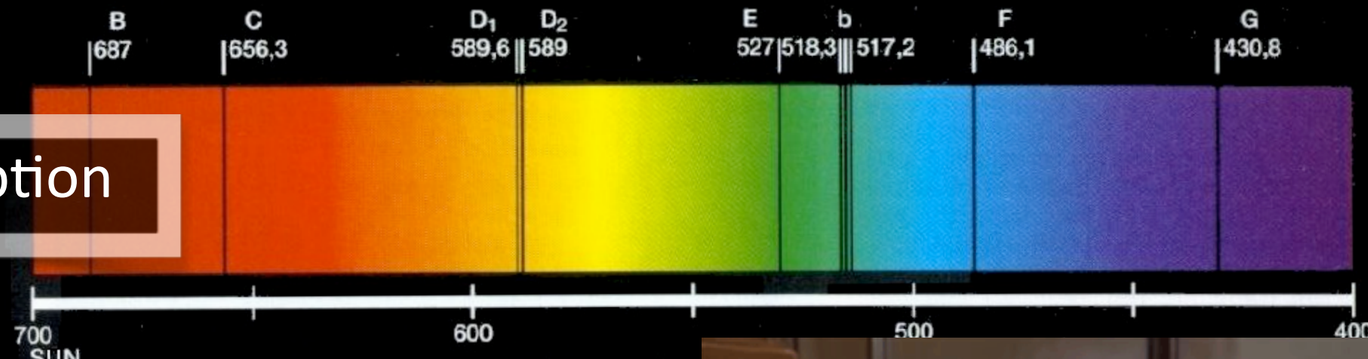
atomic spectra

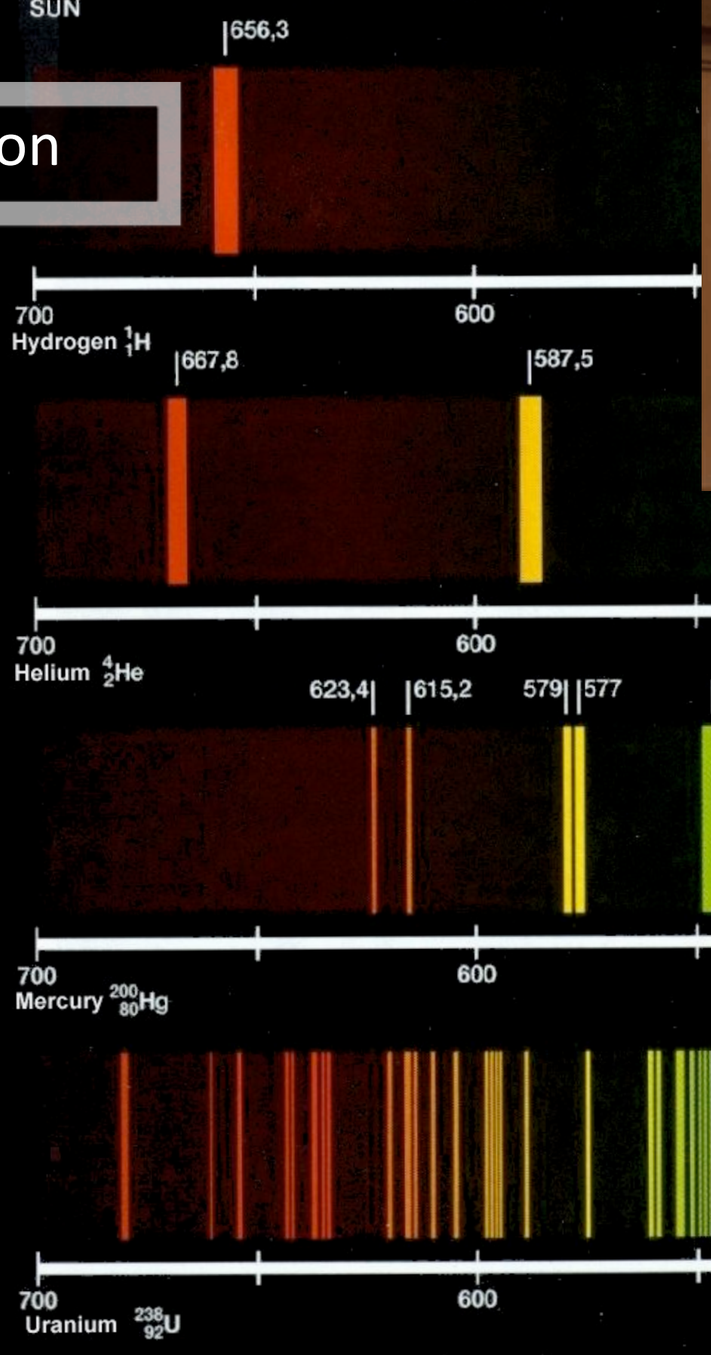
unique fingerprint of the atomic species



absorption

emission



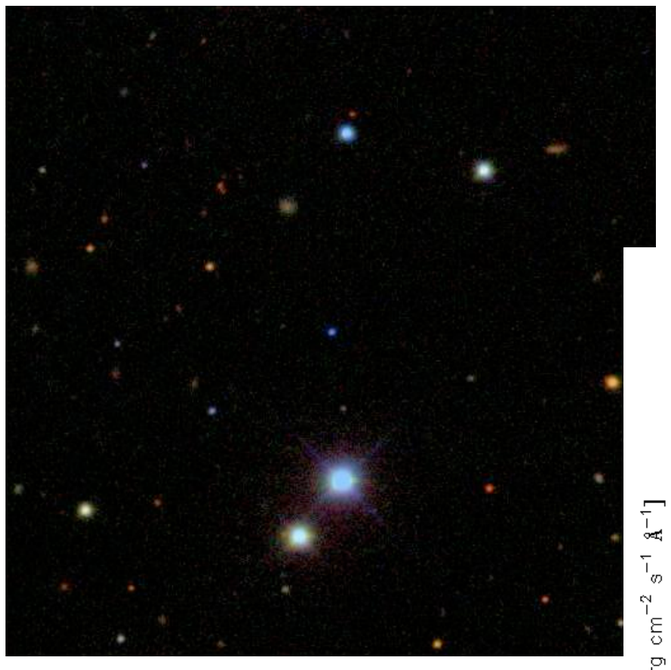


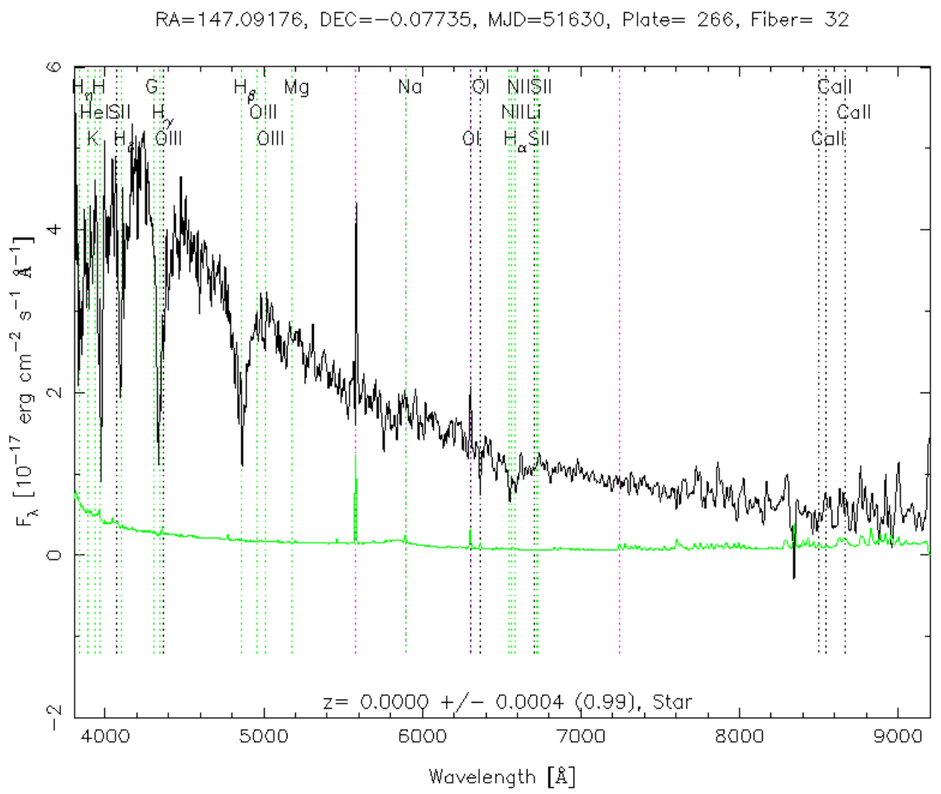
http://www.ruf.rice.edu/~mcannon/Research%20Home/Research%20Home.htm

stars are colorful

line spectra

label stars' outer chemistries





http://cas.sdss.org/dr4/en/tools/explore/obj.asp?id=588848899898278062

Hubble used

the finger-print tool of spectroscopy

plus

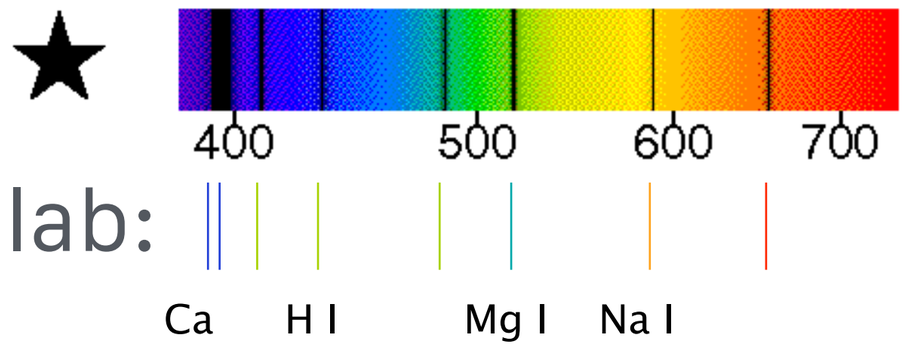
the distance determination tool of Cepheid Variables

His results:

Wavelengths shifted to longer - "**redshifted**"

meaning all of his galaxies seemed to be moving away from us

eg, seemingly, Doppler shifts at work:



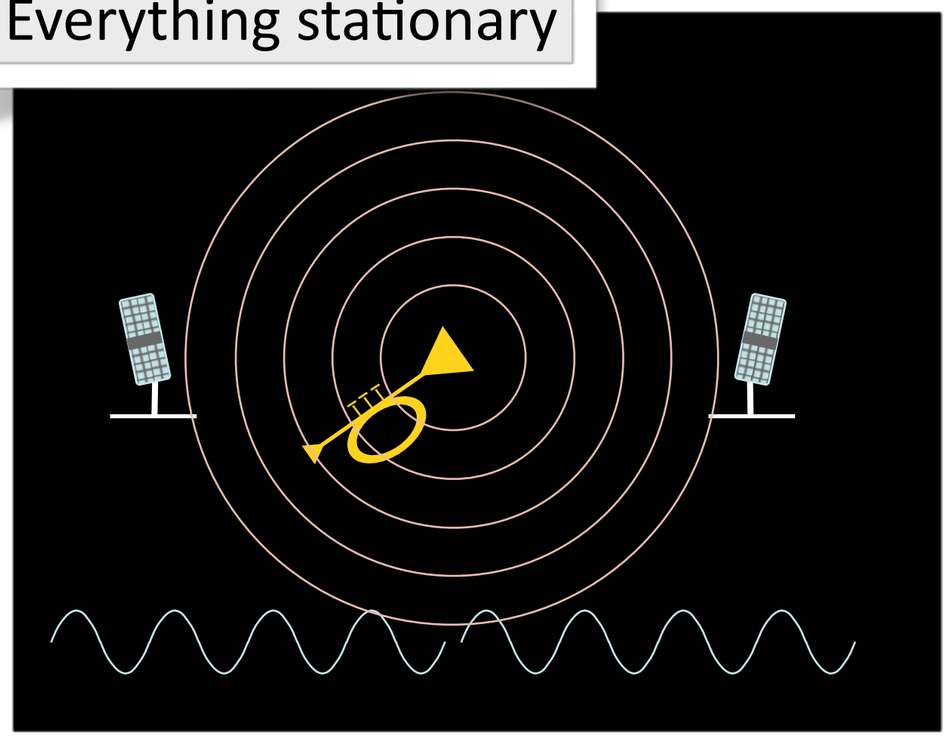
http://www.astro.ucla.edu/~wright/doppler.htm

it seemed like

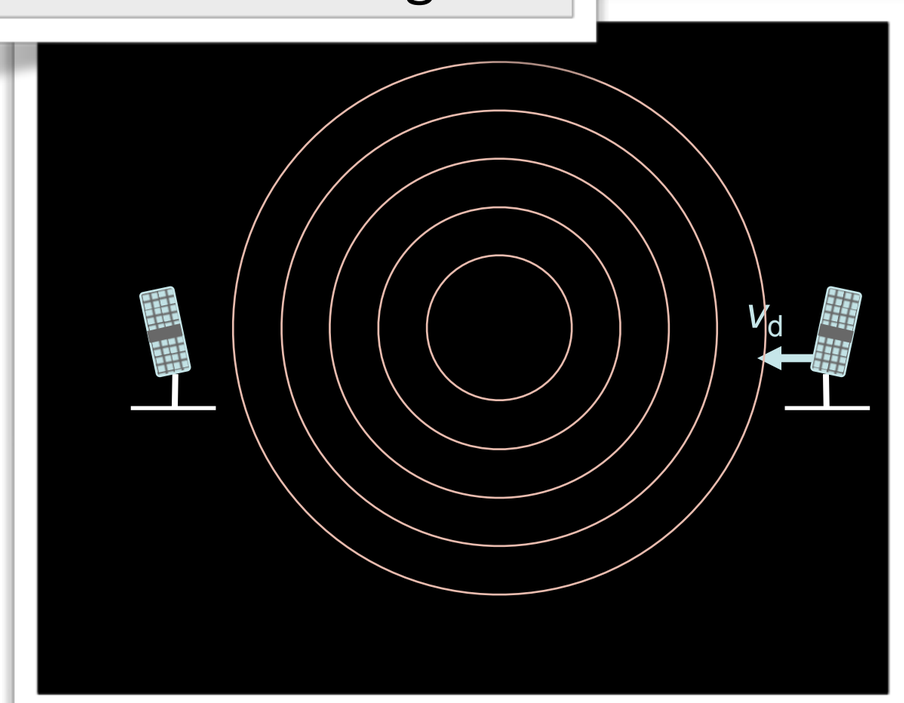
called the "Doppler Effect"

you've all had the experience of listening to the sound of a moving object change pitch

Everything stationary



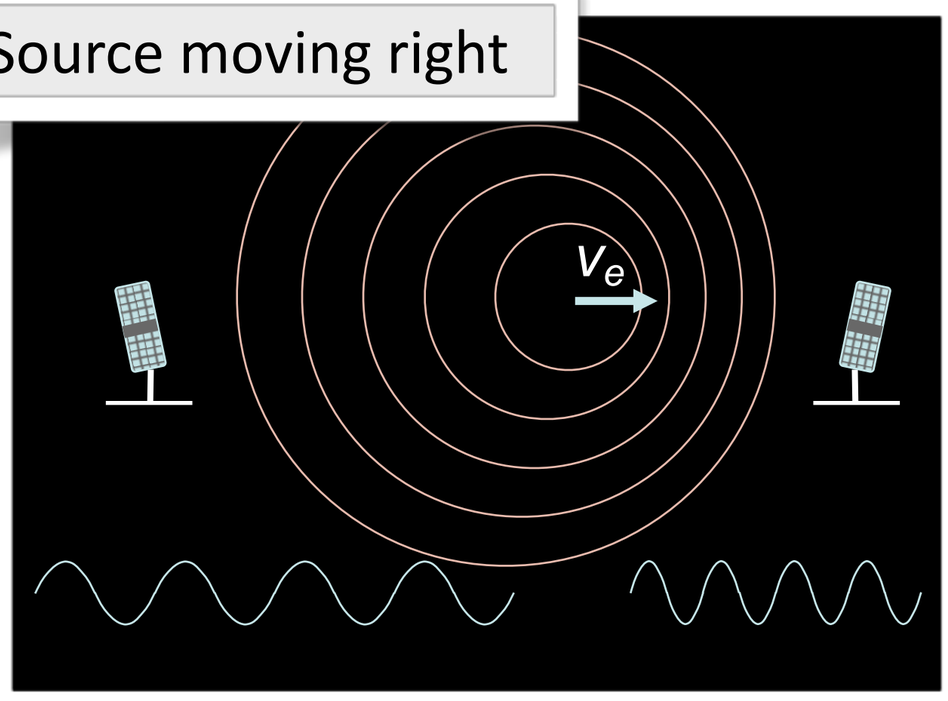
Receiver moving left



the motion toward the left means that R is seeing more peaks in a given time than L, shorter wavelengths @R:

pitch goes up for R

Source moving right



Source moving to Right, shorter wavelengths @R: **pitch goes up for R.**

Sound moving away from L...**pitch goes down for L.**

Lower pitch, longer wavelengths…"red-ish" if light.

Doppler Effect

change of pitch when source of sound

moves towards you

or away from you

v - speed of sound in air

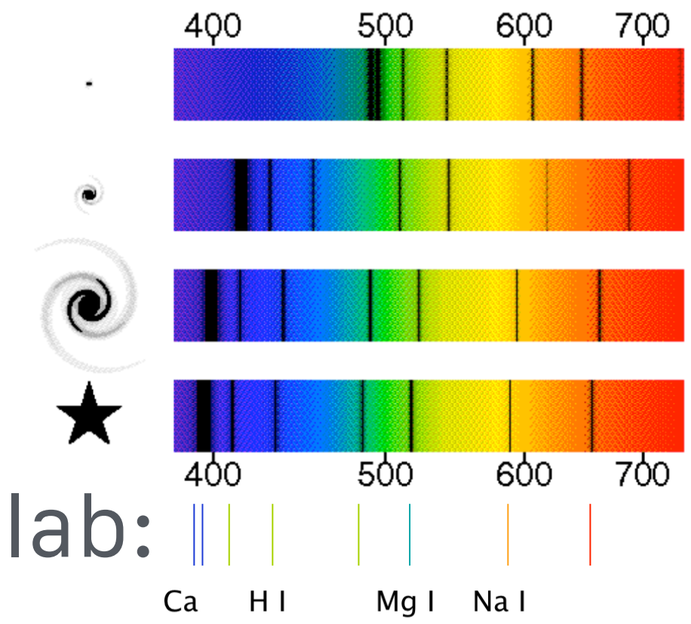
e - emitted

o - observed

$$v = f\lambda$$

$$\frac{v_e}{v} = \frac{\lambda_O - \lambda_e}{\lambda_e}$$

If light?



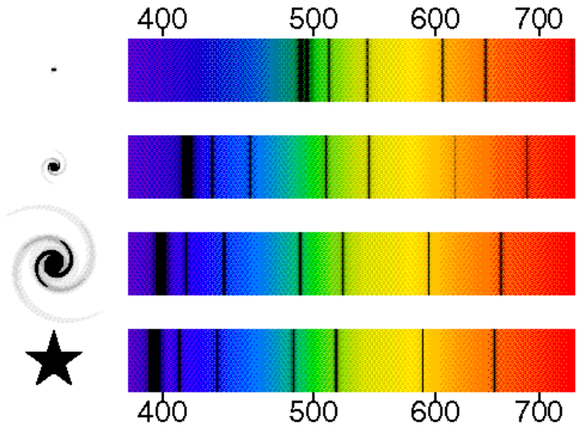
$$\frac{v_e}{c} = \frac{\lambda_O - \lambda_e}{\lambda_e}$$

<—— Observed wavelengths

<—— Lab wavelengths

$\lambda_O > \lambda_e$ so $v_e > 0$ "away from us"

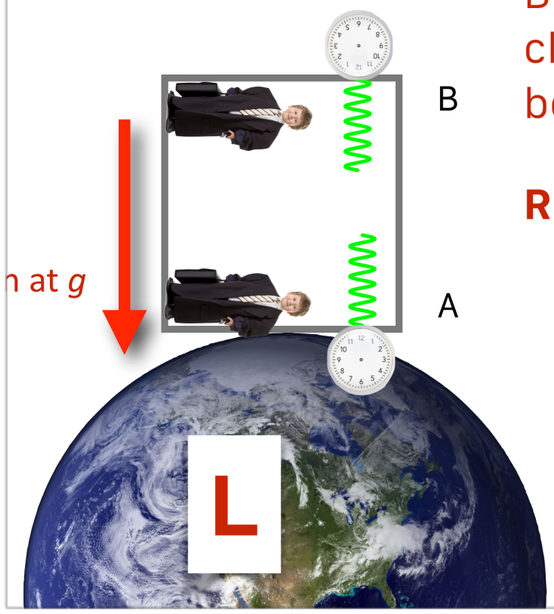
red shifted



this is not that.

but Hubble assumed that it was

remember the Gravitational Red Shift?



B would say that A's clock has longer between ticks:

Runs Slower

"red shift"

receives at say 5 ticks per second

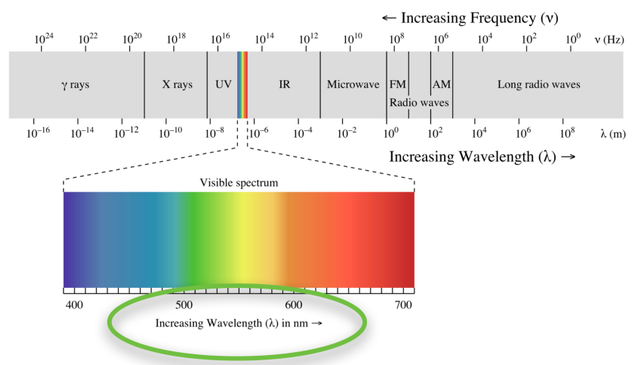
B would say that A's clock has longer between ticks:

Runs Slower

sends at say 10 ticks per second

longer between ticks?

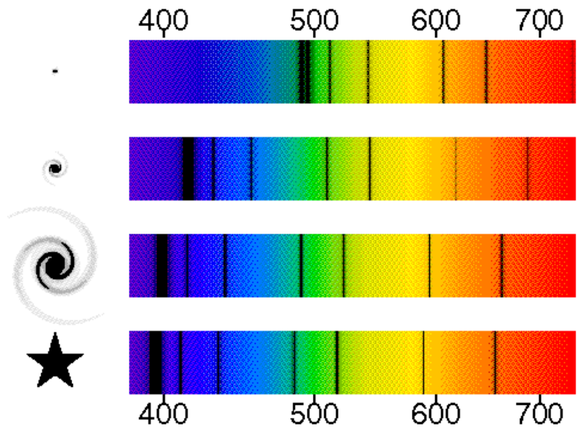
like the wavelength of the light is longer at B than A



an apparent shift to

- a longer wavelength... "red shift"
- and a slower clock

28

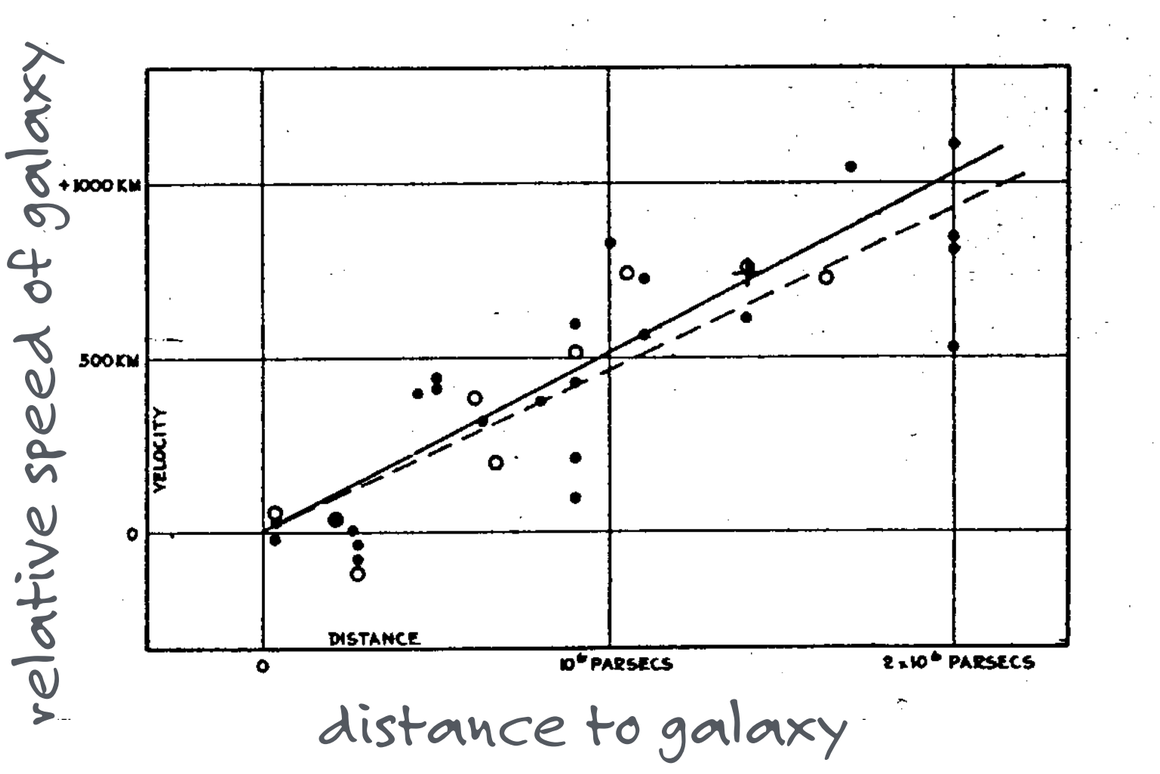


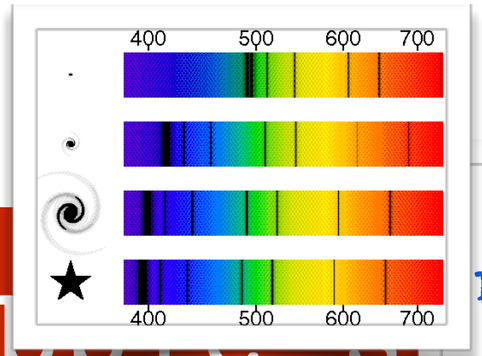
well, this is not that either!

he put two things together

the spectra —> speed

the distance





FROM PRESUMED DOPPLER-SHIFTED SPECTRA

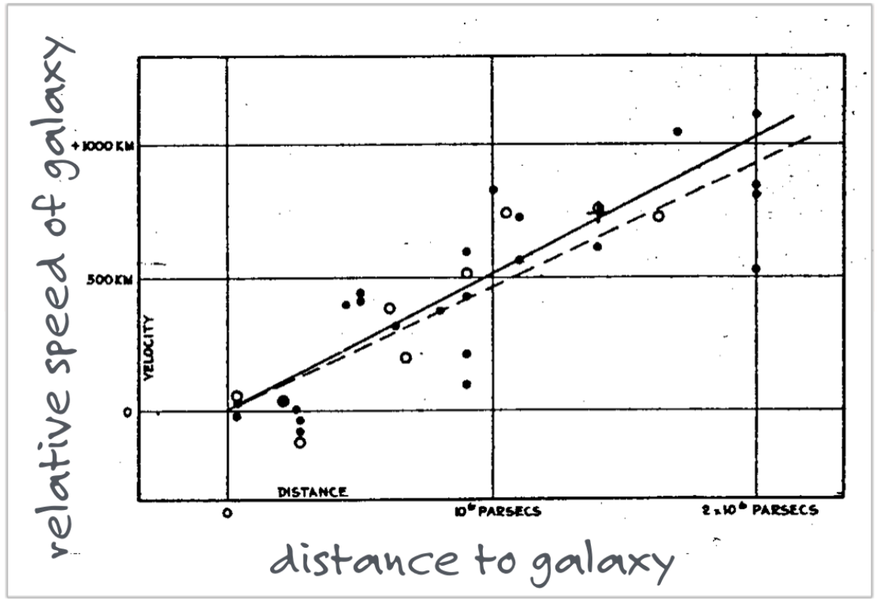
HUBBLE'S CONSTANT = 1/T

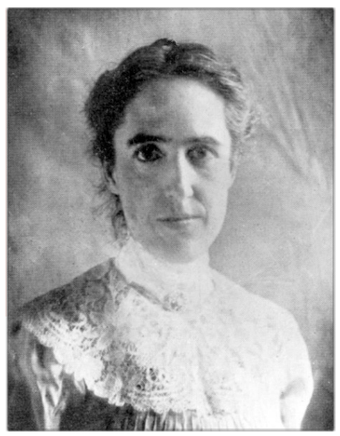
Hubble's

H: a measure of the time a galaxy has been "traveling"

$$v = rH$$

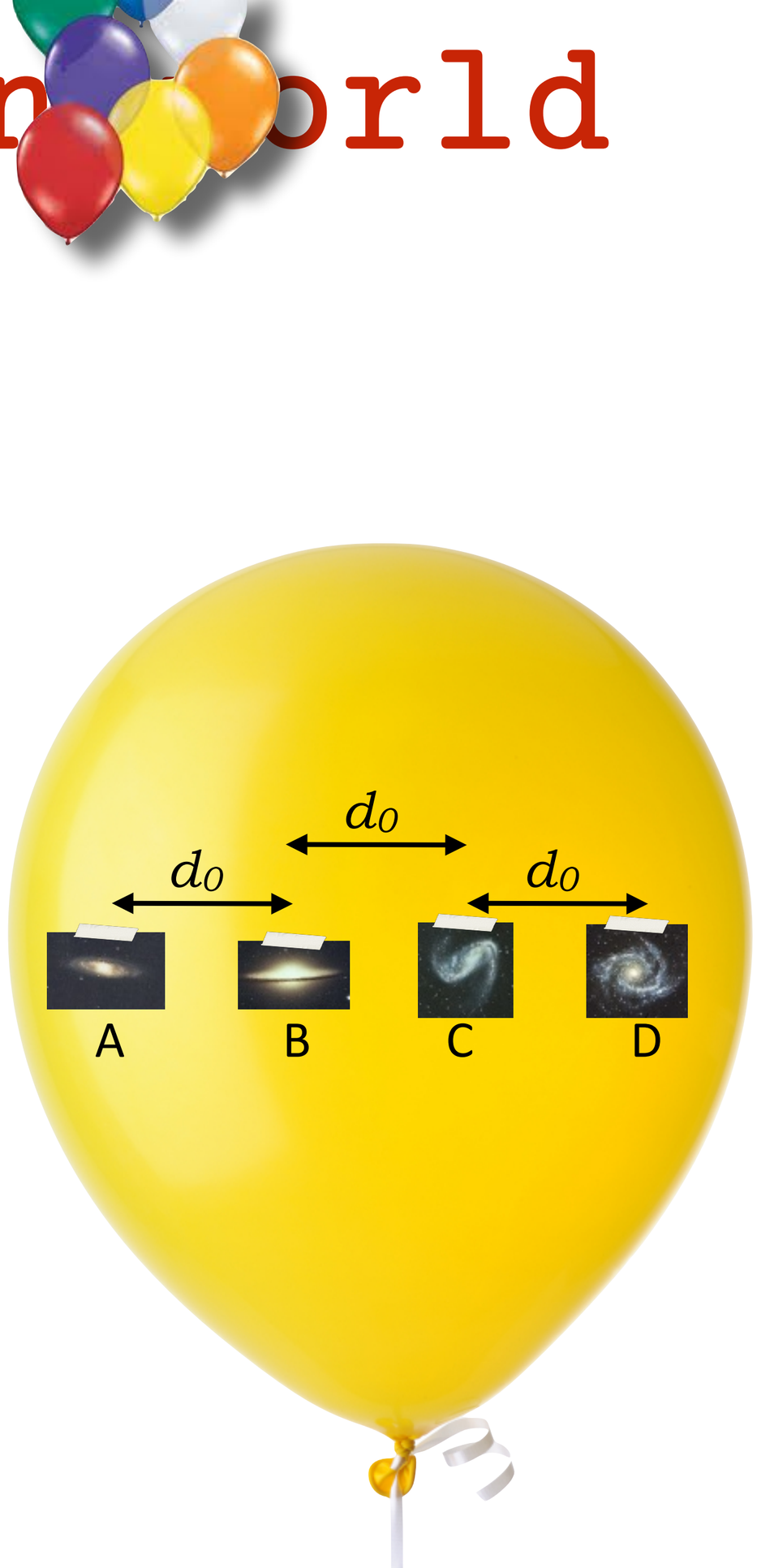
It's a little tricky... Think Balloons.





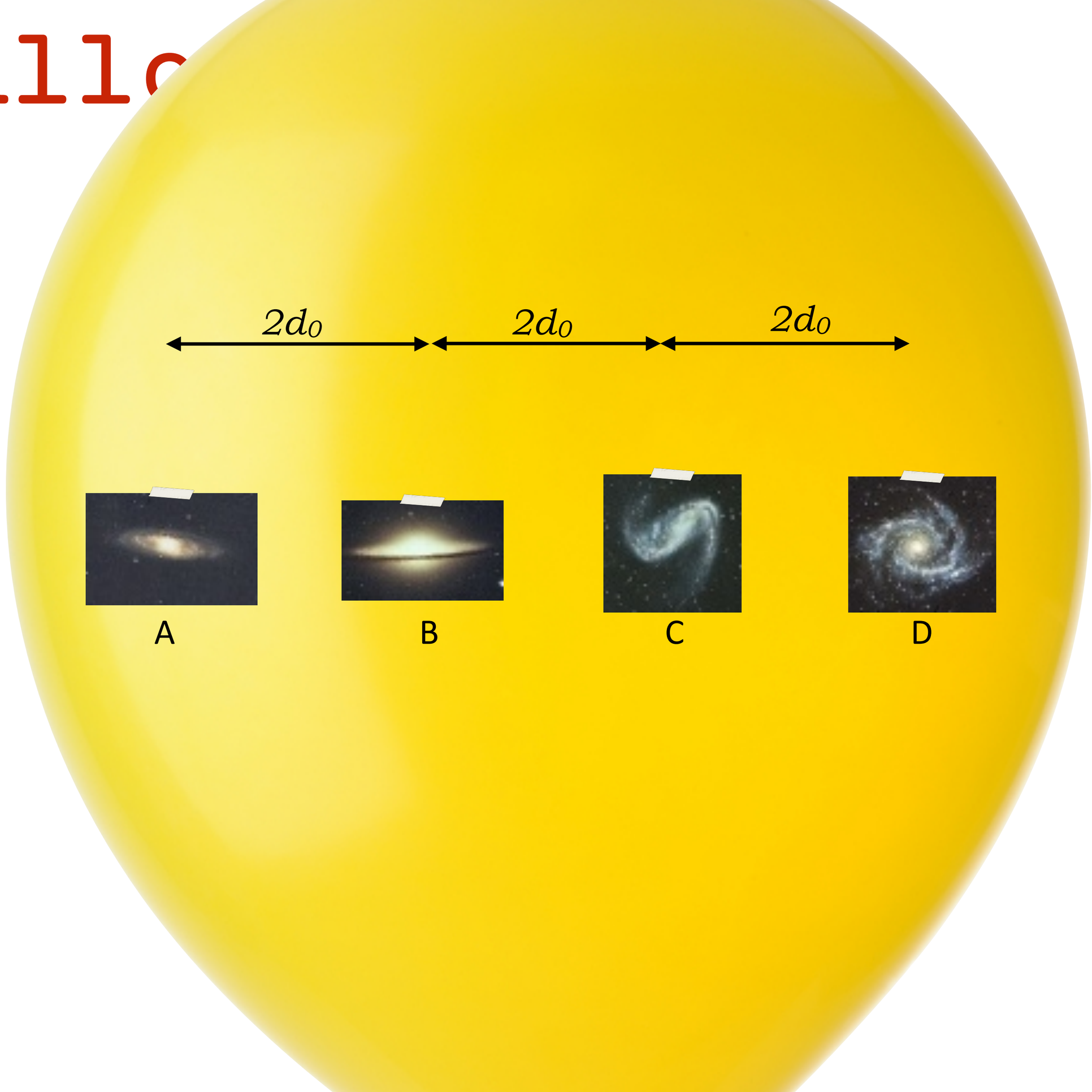
FROM LEAVITT'S CEPHEID VARIABLE RELATION

balloon world



Time 1

ballo



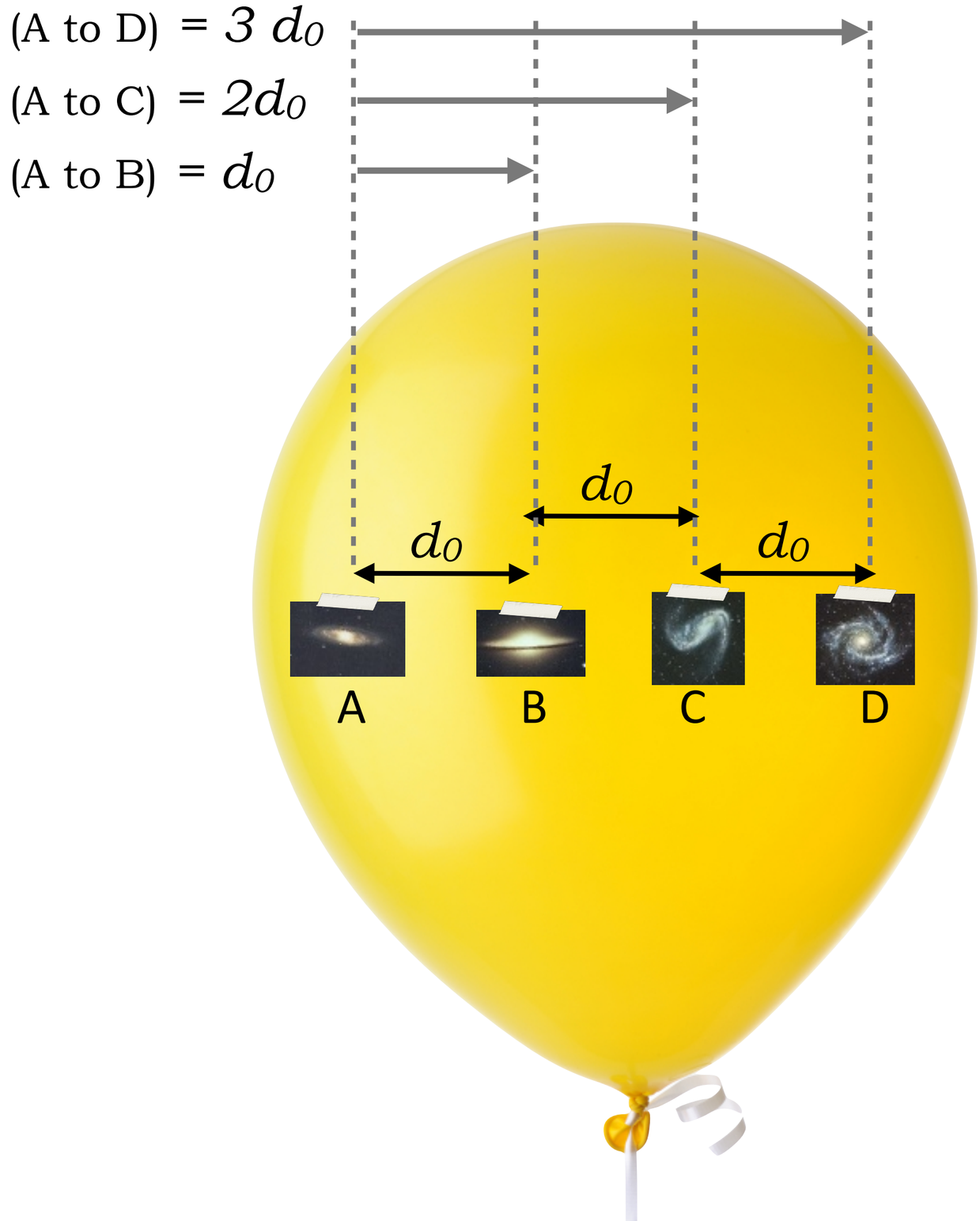
Time 2

$4d_0$ $4d_0$ $4d_0$

A B C D

Time 3

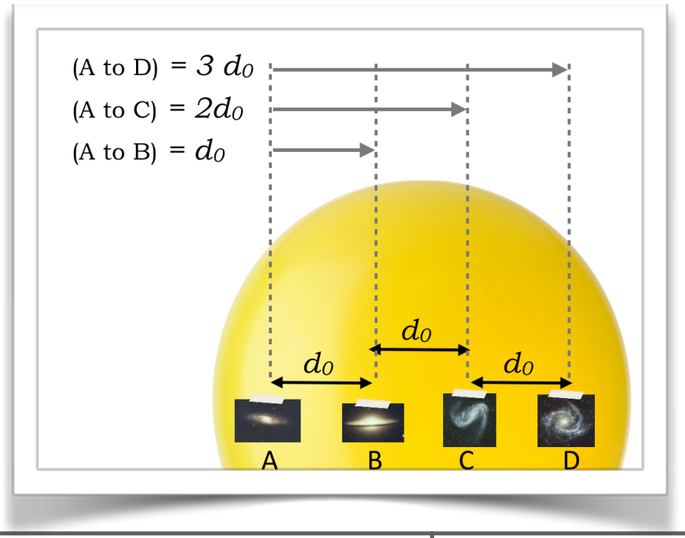
keep track of how far away everything is from Galaxy A



Going to calculate the speed at which **B and C** recede from **A** in Time 1-2 and Time 2-3

what we had

Time 1



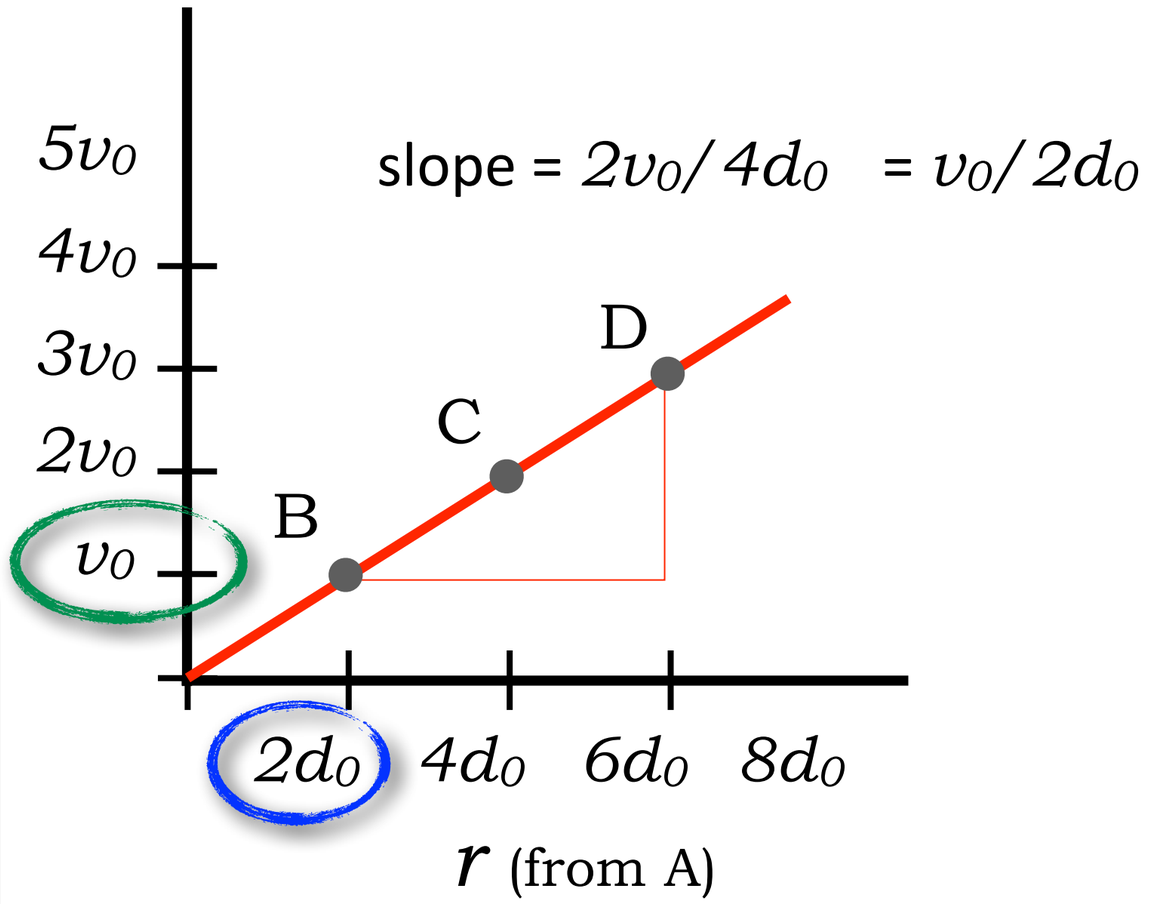
distance, time 1	r = (A to B)= d_0	r = (A to C)= $2d_0$	r = (A to D)= $3d_0$
time 2, Δt later… distance, doubled	$r = 2d_0$	$r = 4d_0$	$r = 6d_0$
Δr, *the difference:*	Δr (A to B)	Δr (A to C)	Δr (A to D)
Δr *between time 1 and 2 =* Δt	$\Delta r = 2d_0 - d_0 = d_0$		
speed $v = \frac{\Delta r}{\Delta t}$	$d_0/\Delta t = v_0$		

plot ‘em up

v

(between A and …)

distance, time 1	r = (A to B)= d_0	r = (A to C)= $2d_0$	r = (A to D)= $3d_0$
distance, time 2	$r = 2d_0$	$r = 4d_0$	$r = 6d_0$
difference:	Δr (A to B)	Δr (A to C)	Δr (A to D)
Δr *between time 1 and 2* = Δt	$\Delta r = 2d_0 - d_0 = d_0$	$\Delta r = 4d_0 - 2d_0 = 2d_0$	$\Delta r = 6d_0 - 3d_0 = 3d_0$
speed	$d_0/\Delta t = v_0$	$2d_0/\Delta t = 2v_0$	$3d_0/\Delta t = 3v_0$



$$v = (slope)r = \left(\frac{v_0}{2d_0}\right) r$$

suppose $r = 5\ d_0$?

what’s v? 2.5 v_0

Also: look at the dimensions of that slope $\left(\frac{v_0}{2d_0}\right)$: $\frac{\text{velocity}}{\text{distance}} \sim \frac{\text{m/s}}{\text{m}} \sim \frac{1}{\text{time}}$

Hubble's Law

a **profound** discovery about the Universe

$$v = rH$$

relation alert: **Hubble's Law**

refers to: $$v = rH$$

example:

Speed of a galaxy is proportional to the distance away from any point.

galaxy NGC1832 is 9.57 x 10^{20} km away, so Hubble's Law says it would be moving at v = 2150 km/s

original results:

$1 \text{ light year} = c \times 1 \text{ year} = 9.5 \times 10^{15} \text{m}$

H = 160 km/sMly

The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space.

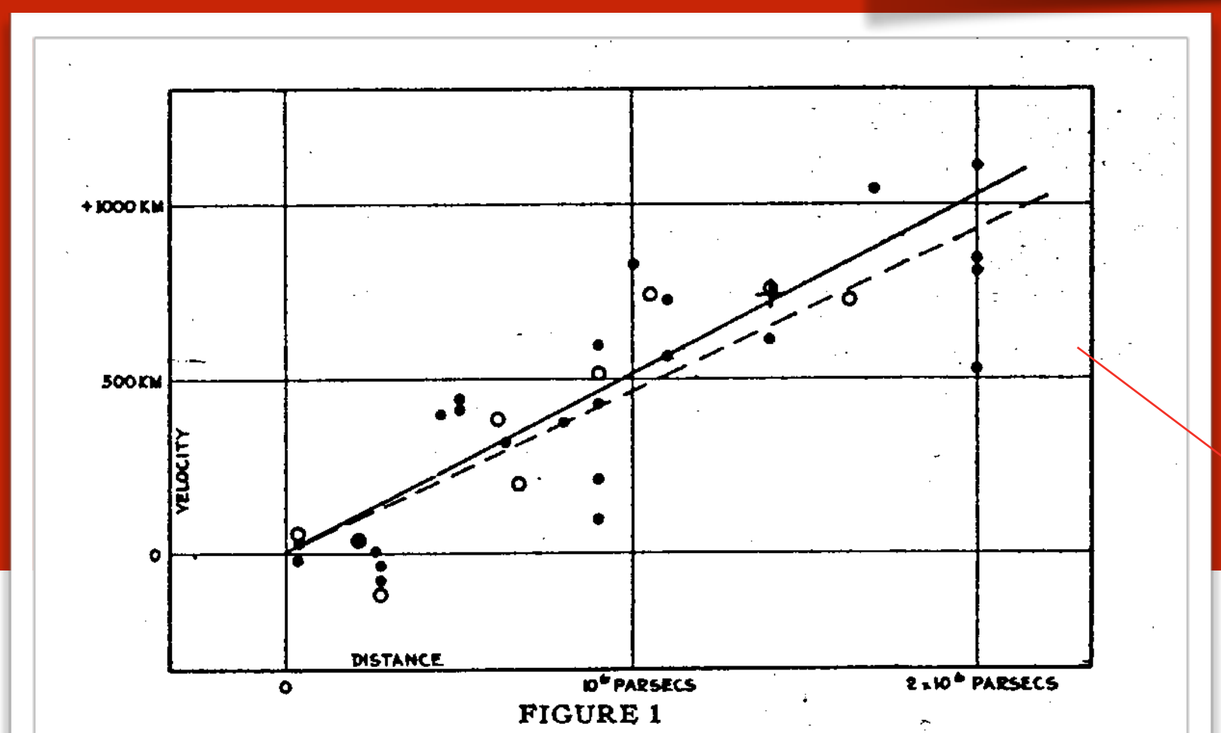
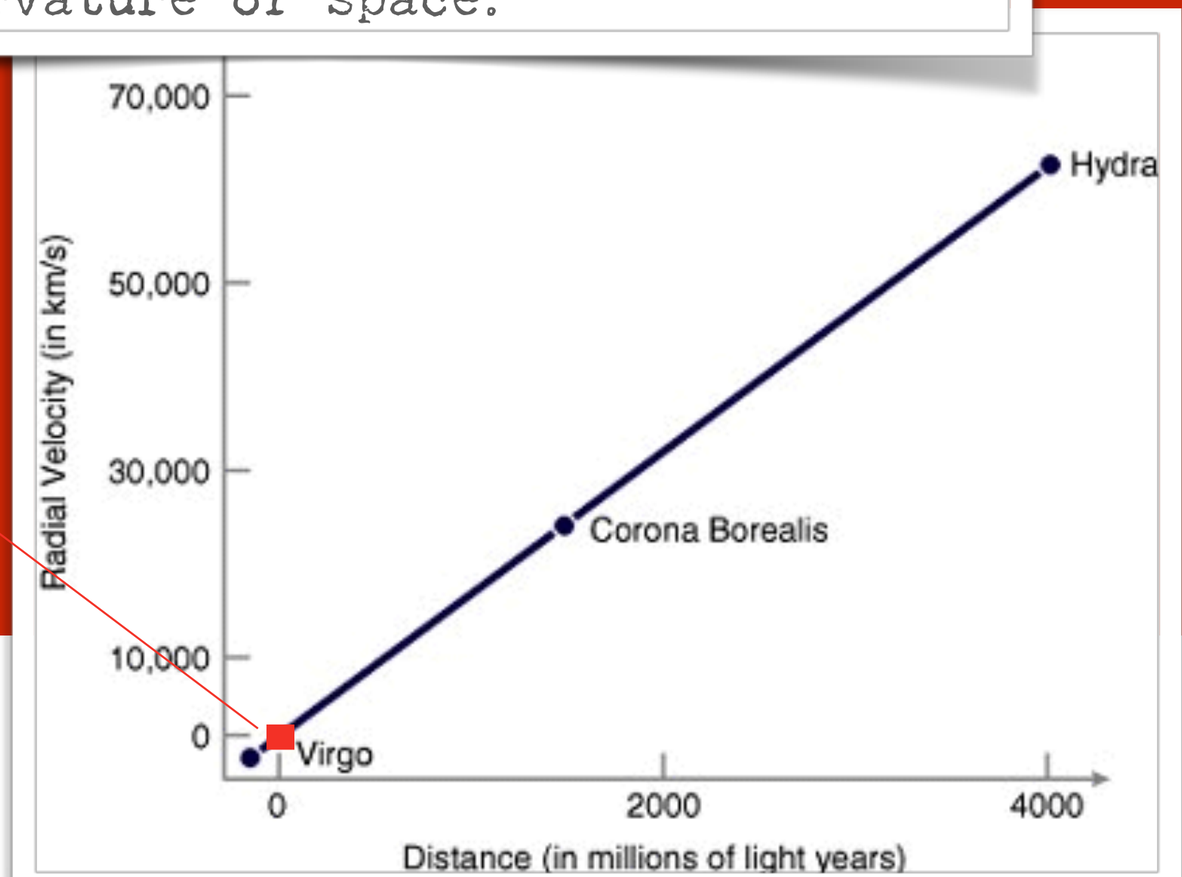


FIGURE 1



So, what does Hubble's Law mean?

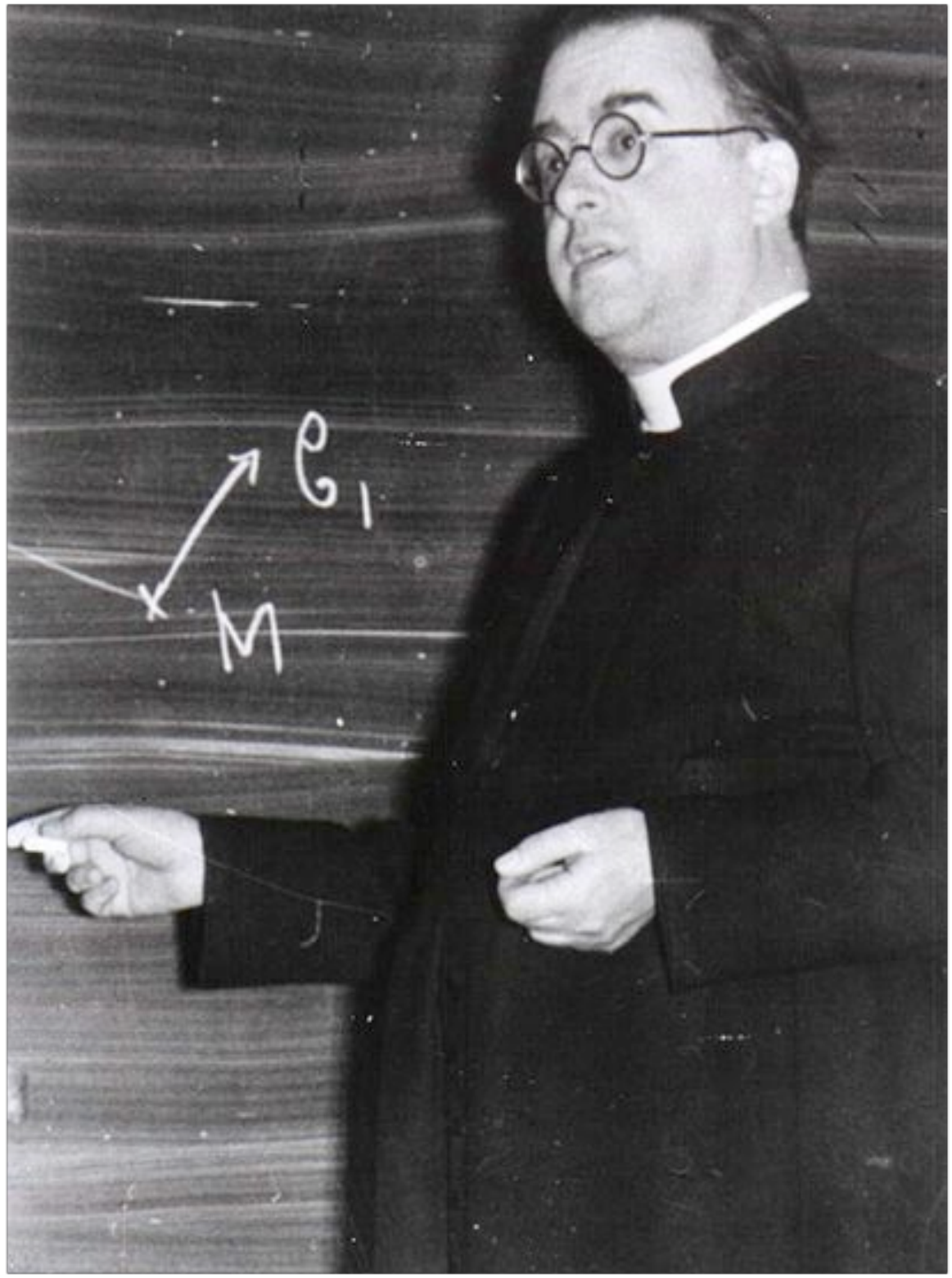
apart from the balloon...

$$v = rH$$

Georges Lemaître (1894-1966)

Father of the Big Bang

I crack myself up.



three kinds of education

war

seminary

physics

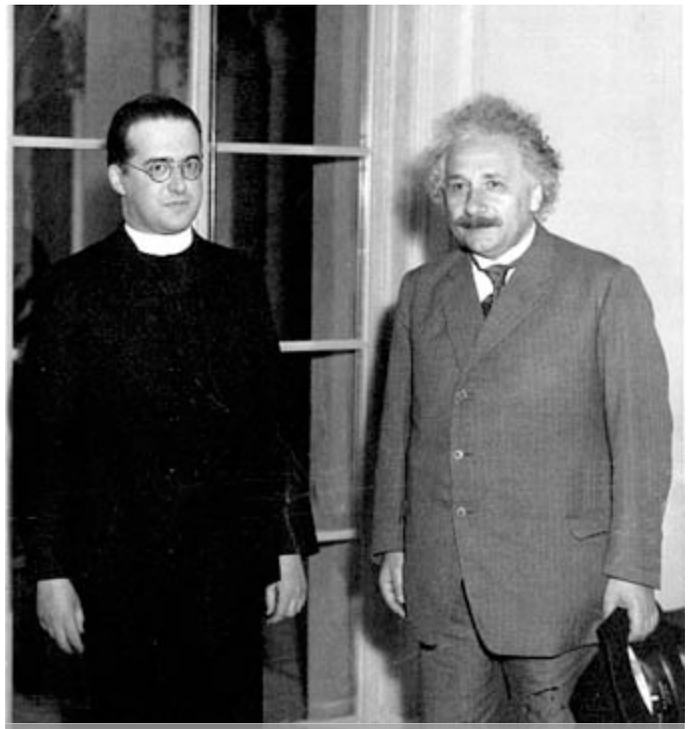
http://www.flickr.com/photos/miguelcalleja/sets/72157604962600986/detail/

1927

Lemaître's model

published obscurely

he believed that General Relativity required an expanding universe



again, Einstein behaved badly

"Your math is correct, but your physics is abominable."

Again, Einstein lets his prejudices

get the better of him

he’d pay for that

In 1927 he published a solution

"A homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae"

Solving $G = T$....with spacetime geometry set free

in an obscure Belgian journal

He predicted the H constant!

his model required the Universe
to be explicitly expanding

When Hubble's results were announced

"brilliant"

he showed it to his old advisor, Sir Arthur Eddington who made it public in 1930:

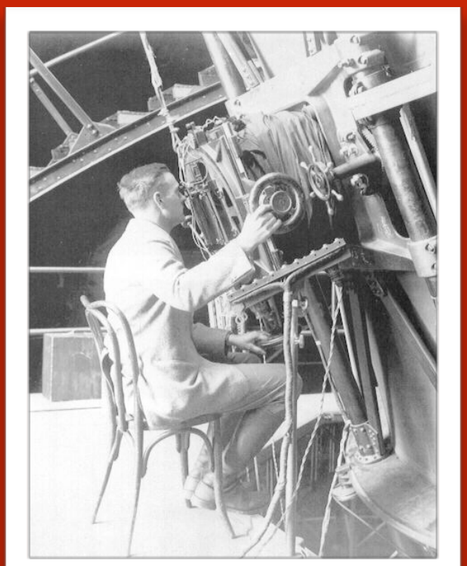
The Lemaître-Eddington model:

constant size, with Einstein's value...and expands from there...

Lemaître was the first to realize that Hubble had demonstrated:

1. spacetime is stretching

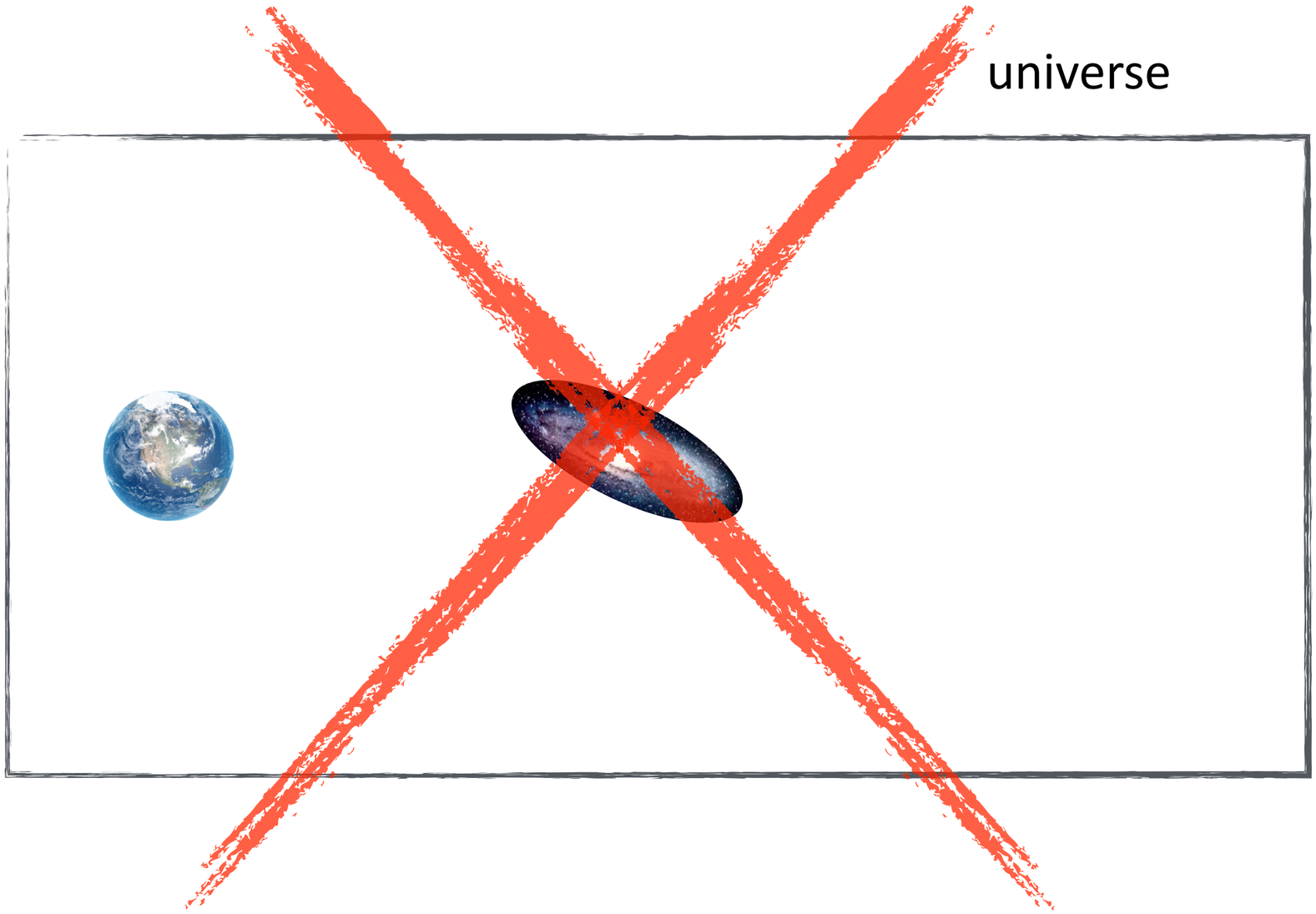
The entire kit and caboodle is expanding



Here’s what it does NOT mean:

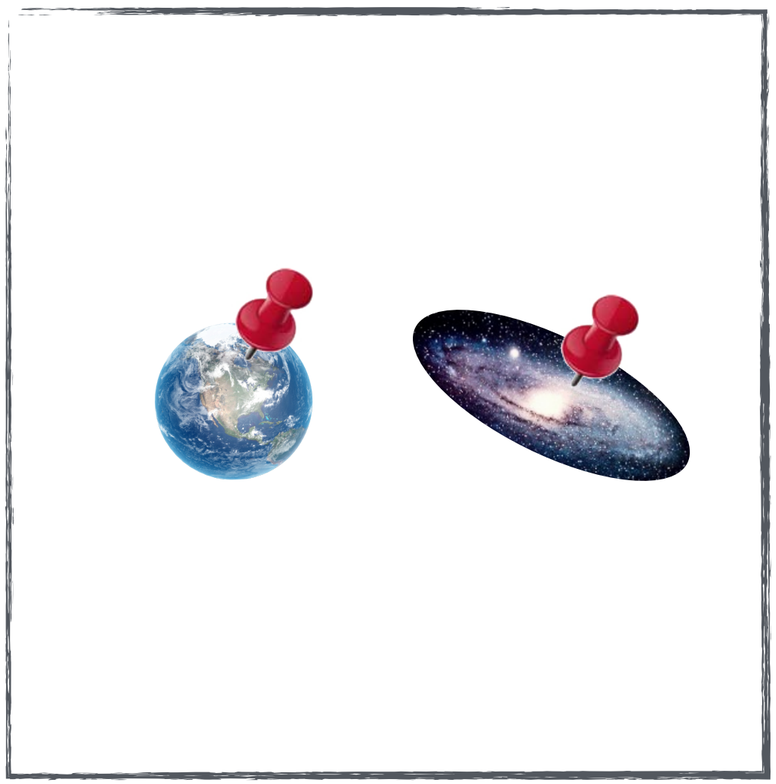
galaxies are not ‘‘moving away’’

inside of the universe



what stretching DOES mean

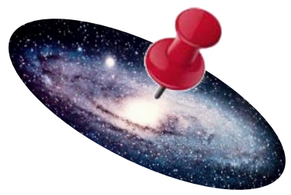
is complicated!



what stretching DOES mean

is complicated!

universe



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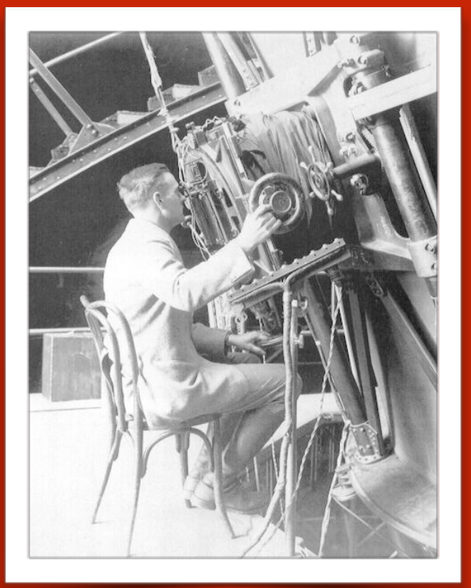
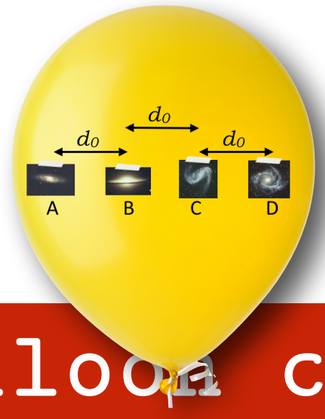


1. spacetime is stretching

The entire kit and caboodle is expanding

2. But then he realized that the current Universe could have come from something smaller



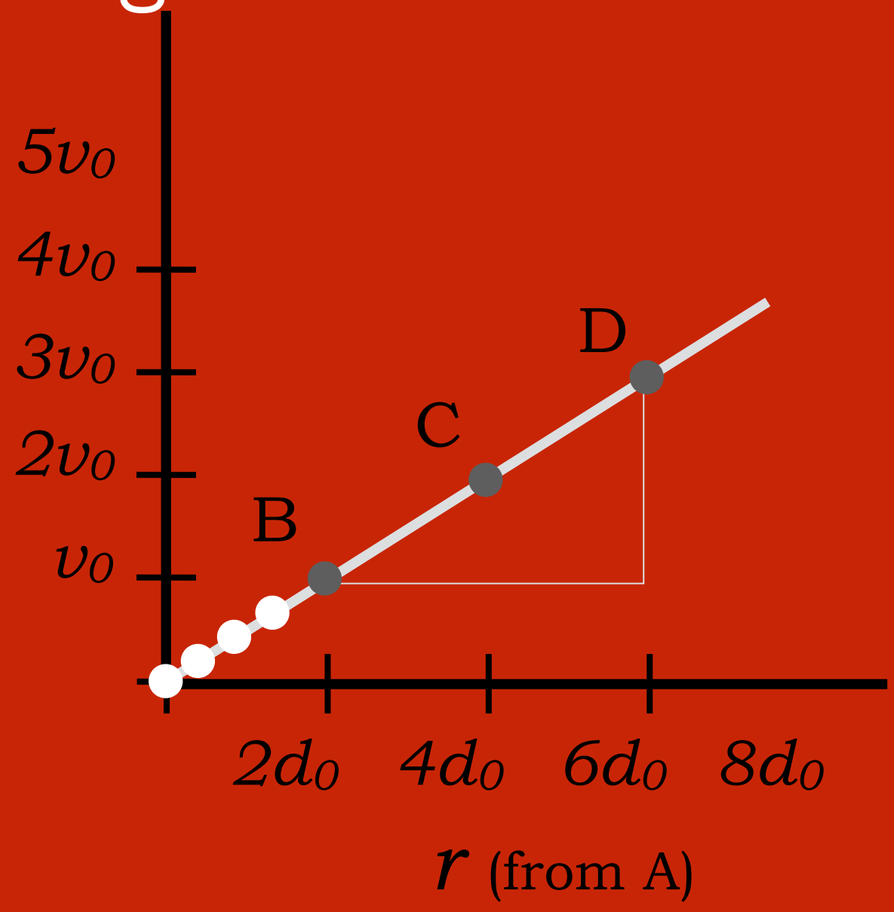
think about the balloon coming from a smaller size

and still smaller

and still smaller

until.

blink



> We can compare space-time to an open, conic cup...The bottom of the cup is the origin of atomic disintegration; it is the first instant at the bottom of space-time, the now which has no yesterday because, yesterday, there was no space.

George Lemaitre, The Primeval Atom, 1946

Lemaître envisioned

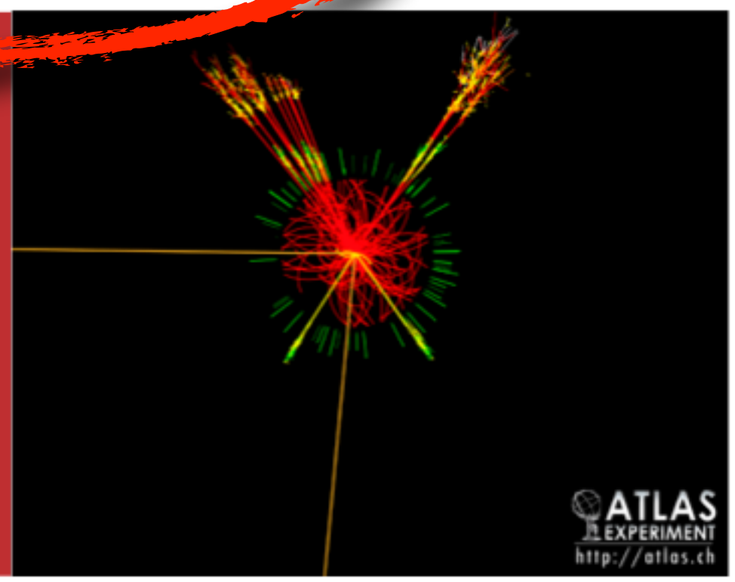
A “primeval atom”

it was the heady times of quantum mechanics and early nuclear physics

He envisioned a fissioning of a big, big nucleus

QUARKS, SPACETIME, and the BIG BANG

spring term 2012



A simulated Higgs Boson event as it might appear inside of the ATLAS detector at the Large Hadron Collider.

think about this.

a Catholic Priest-Theoretical Physicist

envisioning the beginning of the Universe...a "creation story"?

Sir Arthur Eddington states that, philosophically, the notion of the beginning of the present order of Nature is repugnant...I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature.

“

Lemaître: Nature

comment May 9, 1931

Was his theology in the way of his science?

No.

He was explicit in his separation of the science and his faith

And, the respect that his colleagues held for him

did not result in accusations of him pushing his religion into Cosmology

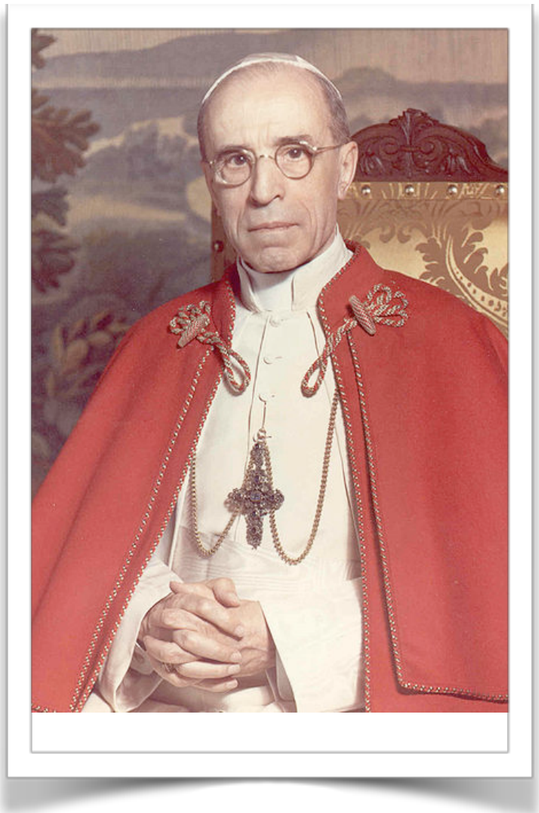
undercut

Lemaître had been very careful

to not mix religion and science

Imagine his panic

when 1951 “Study Week” the Pious XIII made a statement:



. . . contemporary science, with one sweep back across the centuries, has succeeded in bearing witness to the august instant of the primordial Fiat Lux, which along with the matter there burst forth from nothing a sea of light and radiation . . . Thus, with that concreteness which is characteristic of physical proofs, modern science has confirmed the contingency of the universe and also the well-founded deduction to the epoch when the world came forth from the hands of the creator.

Pius XIII, LE PROVE DELLA ESISTENZA DI DIO ALLA LUCE DELLA SCIENZA NATURALE MODERNA*,1951

*TESTS OF THE EXISTENCE OF GOD
IN THE LIGHT OF MODERN NATURAL SCIENCE

Whoa. Lemaître was stunned.

Science and religion to him: two completely different paths

As far as I can see, such a theory remains entirely outside any metaphysical or religious question. It leaves the materialist free to deny any transcendent Being. [1]

We may speak of this event as of a beginning. I do not say a creation.
Physically it is a beginning in the sense that if something happened before, it has no observable influence on the behavior of our universe, as any feature of matter before this beginning has been completely lost by the extreme contraction at the theoretical zero.
Any preexistence of the universe has a metaphysical character. Physically, everything happens as if the theoretical zero was really a beginning.
The question if it was really a beginning or rather a creation, something started from nothing, is a philosophical question which cannot be settled by physical or astronomical considerations. [2]

[1] Solvay Conference 1958

[2] quoted in: Godart and Heller, Cosmology of Lemaître, 67

Lemaître

WWII was hard on Belgium

after the war, Lemaître did not go back to first-principle cosmology

but he pioneered scientific computing on cosmological parameters before anyone in the 1950’s

Like Copernicus

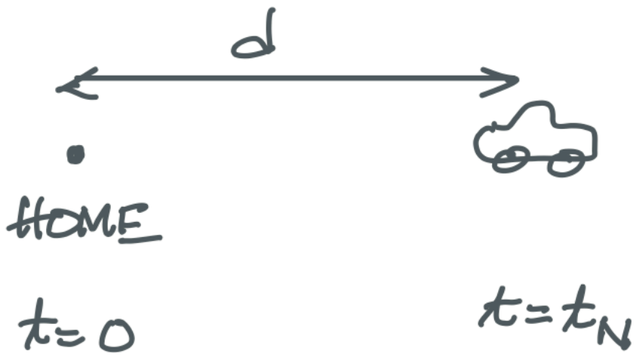
Within days of his death, Lemaître learned of Penzias and Wilson’s discovery of the cosmic microwave background consistent with the Big Bang

June 20, 1966

Hubble Constant

critical measurable parameter in cosmology

speed and distance!



$d = 300\,\text{mi}$ & $v = 60\,\text{mph}$

how long? -- what's t_N ?

original results:

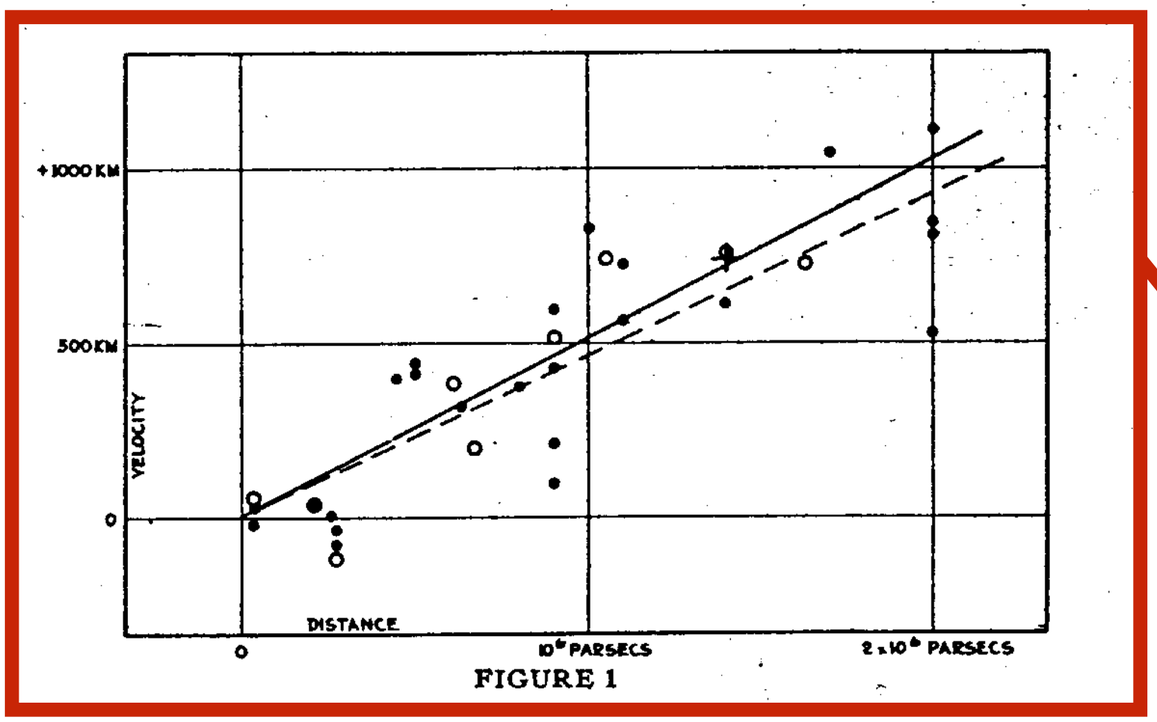
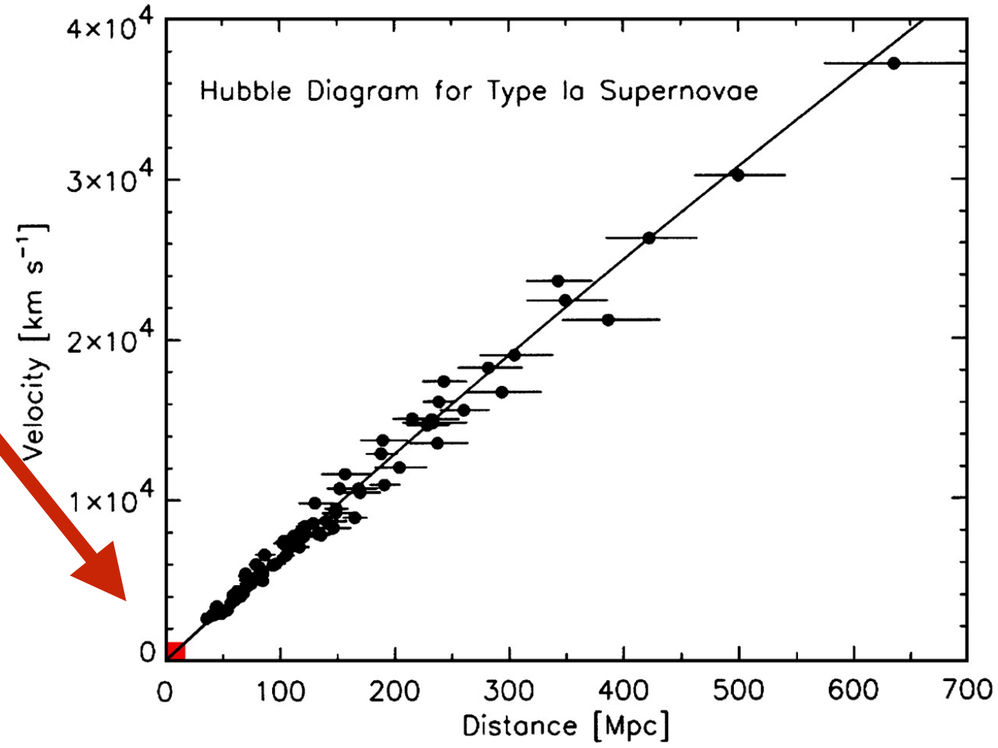


FIGURE 1



1 megaparsec (Mpc) = 10^6 parsec = 3.26 x 10^6 light years = 3.086 x 10^{16} m

so 1/H measures the age of the universe*

How did he do? $H = \frac{160\ m/s}{M\,ly}$ 1929

$1\ ly = 9.5 \times 10^{15}\ m$.

* first-pass

a big “uh oh”

almost immediately after Hubble’s measurement

oops.

geologists already understood that the Earth was at least 3 By old.

That required some work!

Refinements found a number of assumptions in need of updating

for example...there are 2 kinds of Cepheid Variable stars, and other issues

This is the beginning of quantitative Cosmology.

Measuring the Hubble Constant is an important cottage industry in astronomy

current best result:

$H_0 = 67.66 \pm 0.42$ km/sec/Mpc

$H_0 = 2.2 \times 10^{-18}$ s^{-1} = 4.5×10^{17} s = 14.5 By*

The subscript “0” means: “Now”

* first-pass: The inverse of the Hubble Constant isn’t necessarily the age of the universe

1 megaparsec (Mpc) = 10^6 parsec = 3.26 x 10^6 light years = 3.086 x 10^{16} m

what do the red shift(S) actually imply? &
what was Lemaître's insight?

not doppler

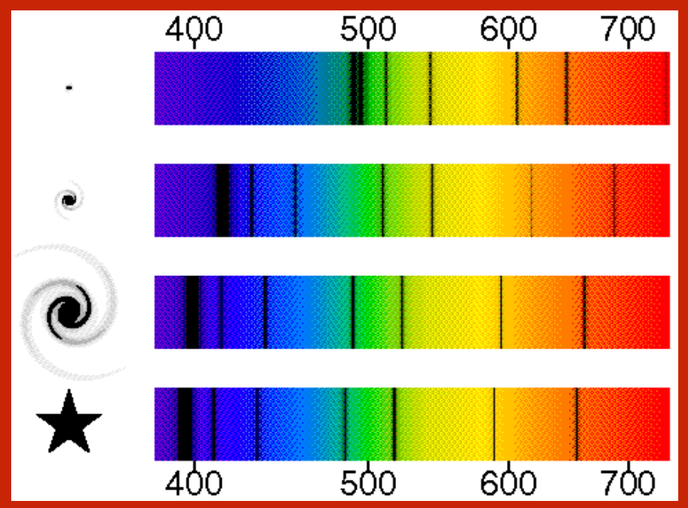
not gravitational

here's **what it is.**

the “red shift”

isn’t a Doppler velocity

it’s geometry

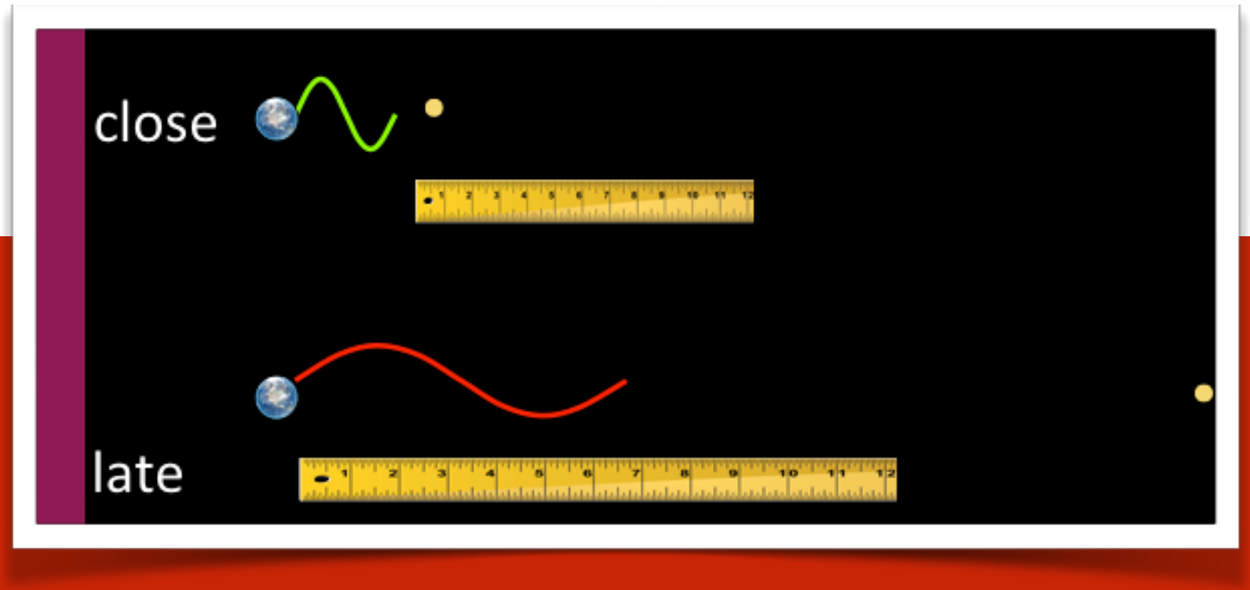


close

late

early

The further away



the more red-shifted its spectrum will be

and the faster it will appear to be receding

the older it will be

and the younger it will appear to be!

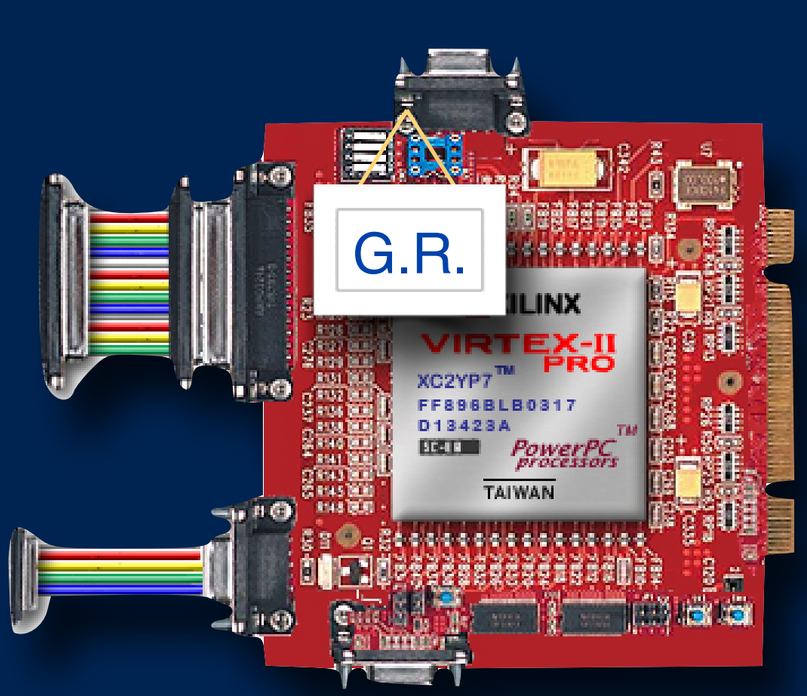
here’s how this is described

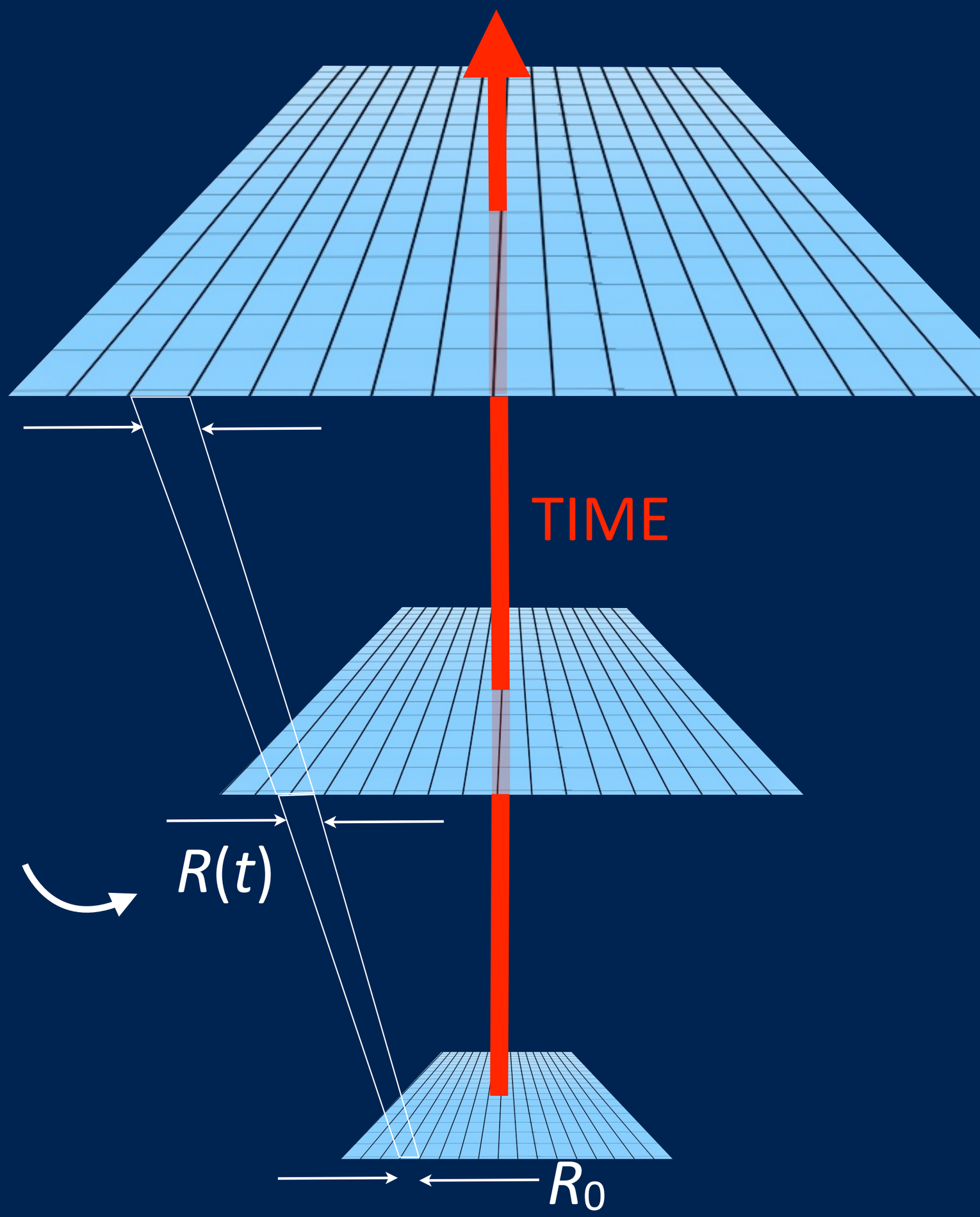
a little technical, but you can do it!

energy/mass/pressure

energy/mass/pressure

$$G = T$$

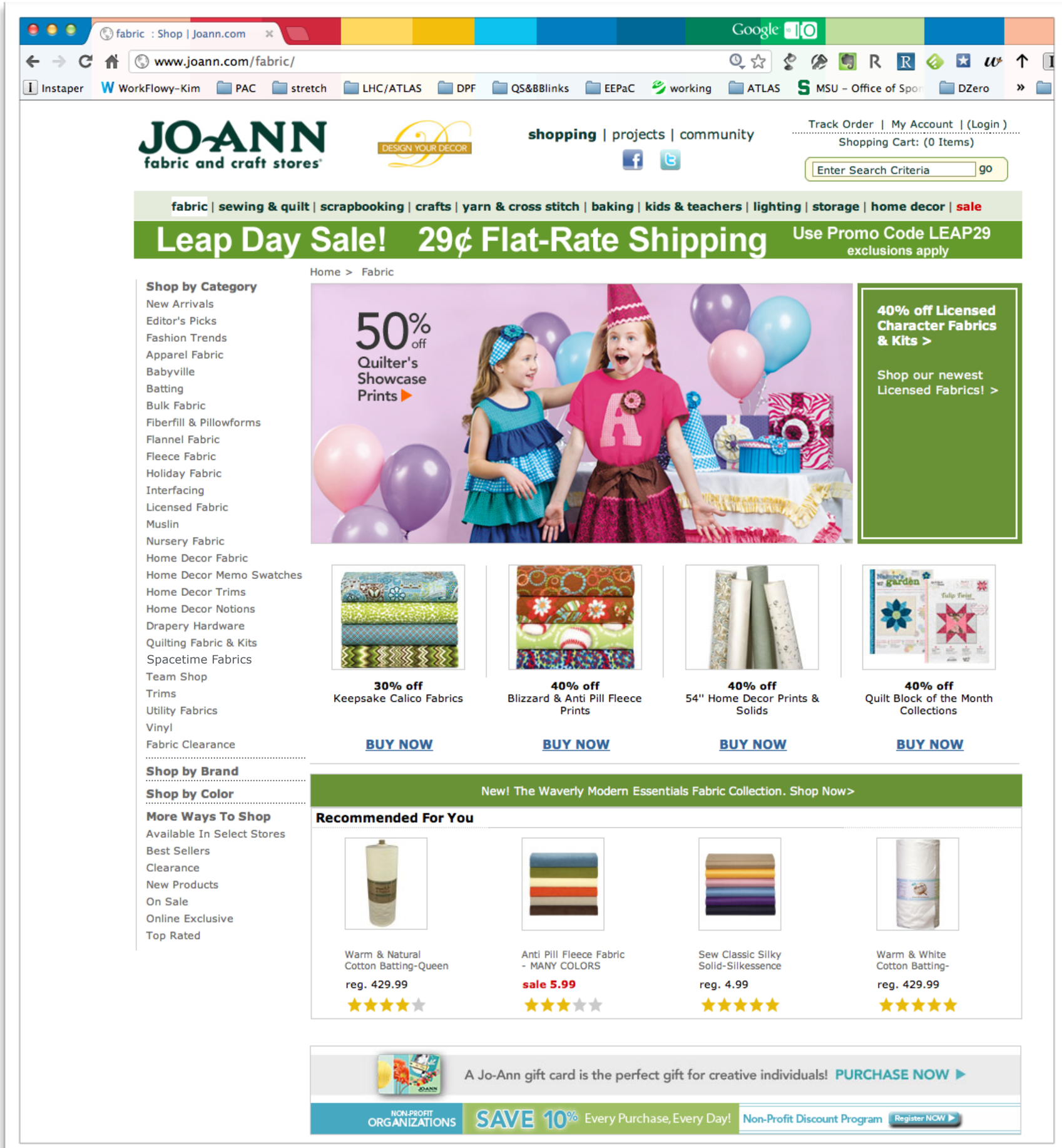




Then a spiritual moment occurs.

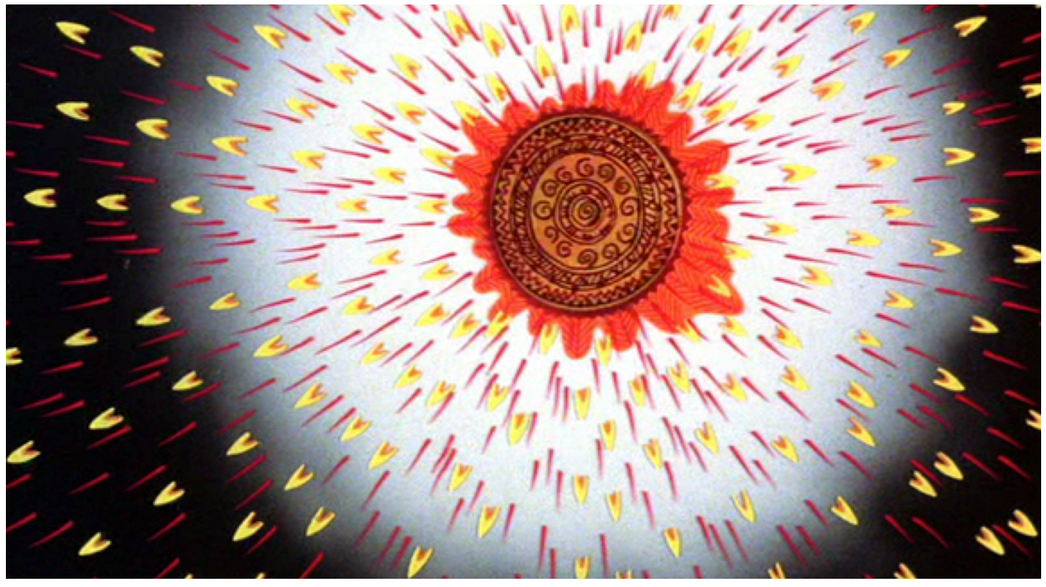
involving spandex.

fabric of spacetime



So, we need 4 deities:

dark specter from power rangers from space



lord firth watership down

Arceus from Pokémon

fujin from Mortal Kombat

What’s R(t)?

The “scale factor”

the stretchiness of spacetime

The Friedman, Walker, Robertson models

Friedman's and Lemaître's work was expanded on by Howard P Robertson and Arthur G Walker in 1936

They found exact solutions to the Einstein equations, using the Friedman techniques.

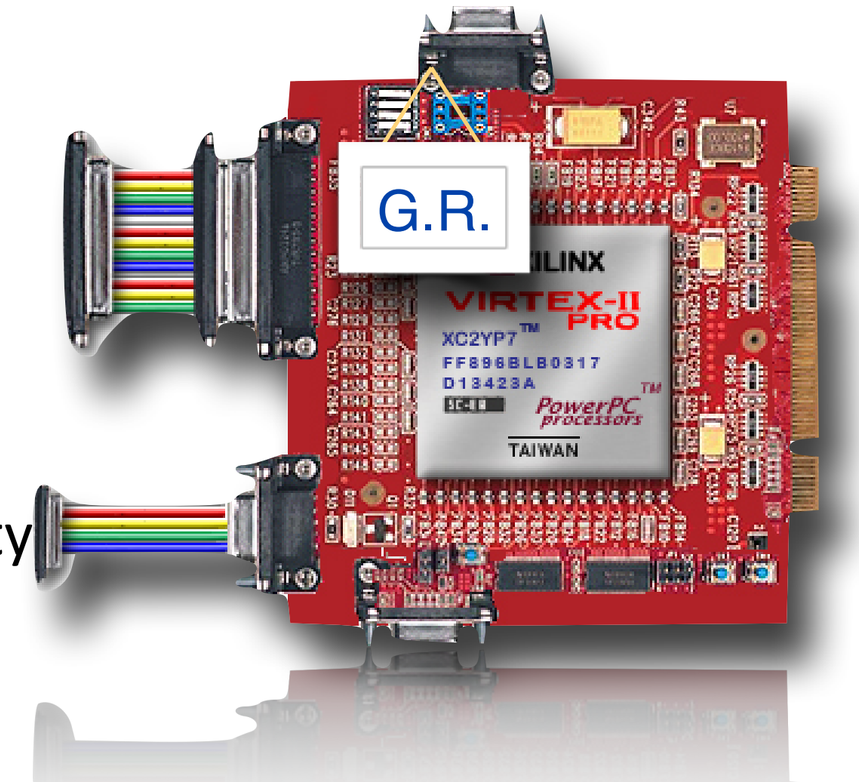
Their model of cosmology is variously called the:

FWR model

FLWR model

Standard Model of Cosmology

$$G + \Lambda = T$$
$$G = T$$

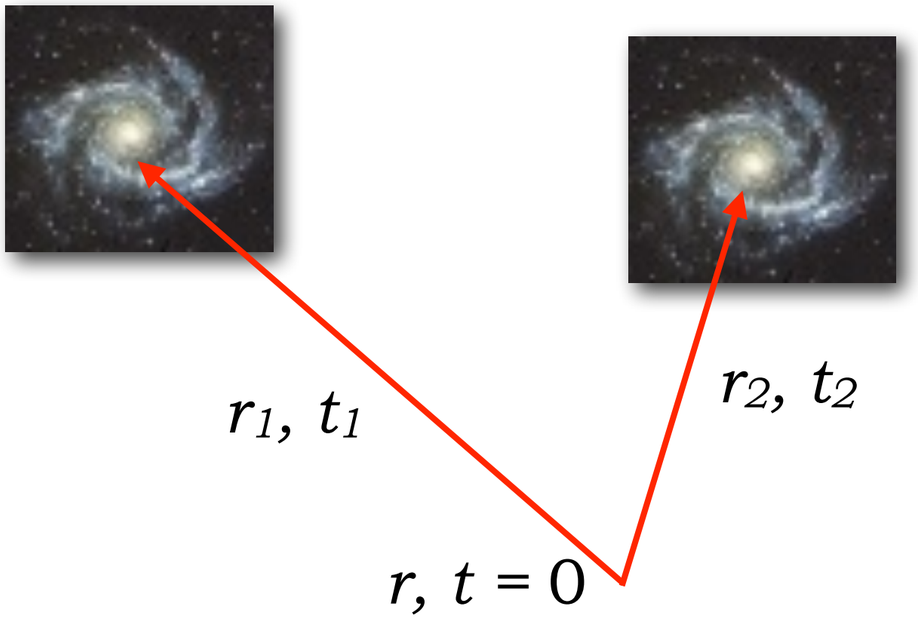


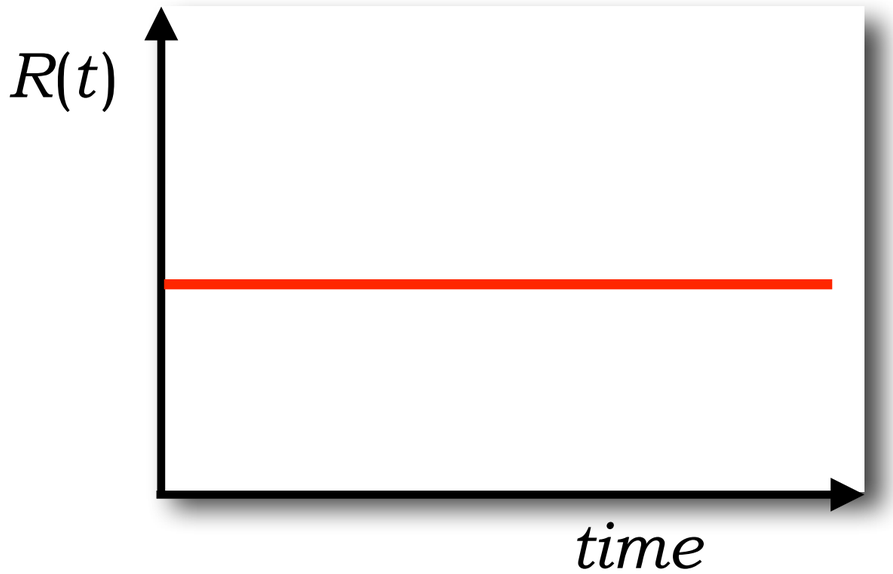
varying assumptions, k, density

can catalogue the behavior of R

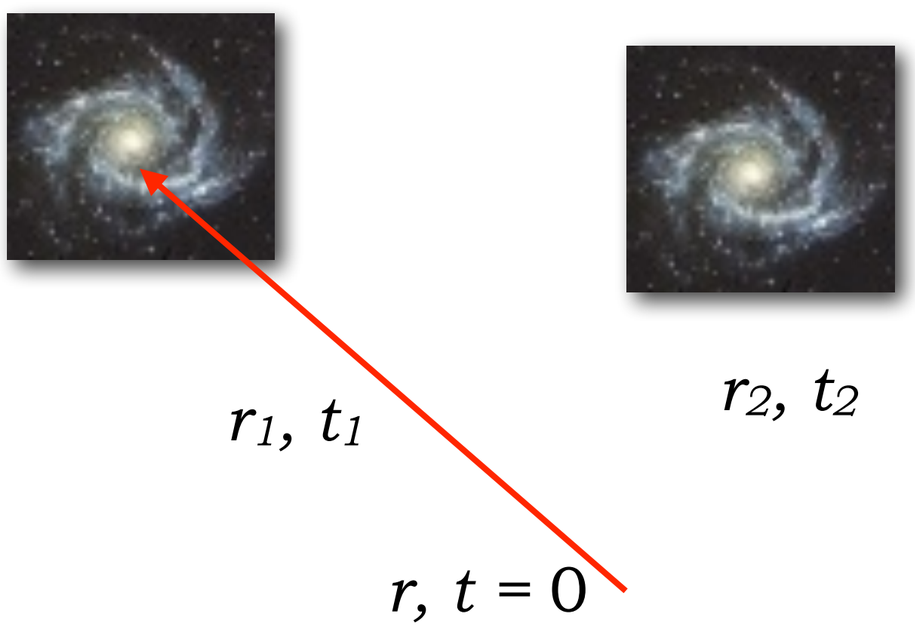
for different choices of the Cosmological Constant and k

Einstein's original model





What did Einstein say would be the case?



Static...for which he needed a particular value of the Cosmological Constant

$$\Lambda_E = \frac{4\pi G\rho}{c^2}$$